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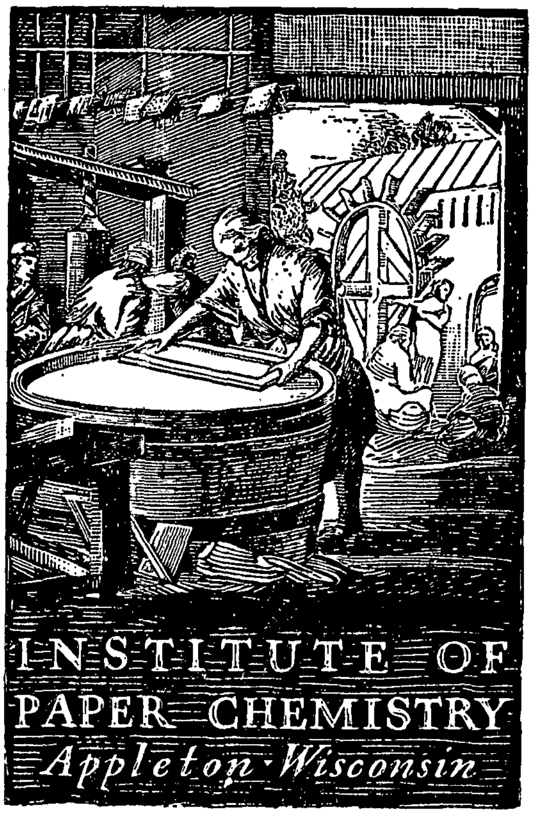

RELATIONSHIP BETWEEN HIGH-LOW FLUTE FORMATION AND THE PROPERTIES OF THE CORRUGATING MEDIUM

Project 2696-6

Report One

A Summary Report

to

FOURDRINIER KRAFT BOARD INSTITUTE, INC.

December 24, 1969

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THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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RELATIONSHIP BETWEEN HIGH-LOW FLUTE FORMATION AND THE PROPERTIES OF THE CORRUGATING MEDIUM

SUMMARY

This study was initiated to study the relationships between various corrugating medium properties and the occurrence of high-low corrugations. For this purpose, twenty-one 26-lb. semichemical mediums were selected so as to provide a wide geographical representation of mediums included in the FKI medium base-line study.

The corrugating mediums were fabricated into A-flute single-faced board on the Institute's corrugator using (a) normal operating conditions which usually produce a minimum of high-lows and (b) adverse operating conditions known to give more pronounced high-low corrugations. Thus, the adverse conditions give an indication of how a given medium will perform under less than "ideal" corrugating conditions.

The single-faced board was evaluated to determine the difference in height between adjacent flutes (average flute height difference). Relationships between the average flute height difference and various medium properties were then studied.

Based on the results obtained herein, the following conclusions may be drawn:

SIMPLE CORRELATIONS

1. The following properties exhibited statistically significant correlations at the 0.10 level or better with average flute height differences (listed in descending order of correlation coefficient):

a. Normal operating conditions

(1) Alcohol-benzene extractives (r = -0.53)

(2) Formation (r = -0.44)

(3) "Elastic" work (product of tensile strength times recoverable stretch) (r = 0.44)

(4) Tensile work (r = 0.42)

(5) Tensile strength (r = 0.40)

b. Adverse operating conditions

(1) Tensile strength (r = 0.52)

(2) Tensile work (r = 0.47)

(3) "Elastic" work (r = 0.46)

(4) Tensile stiffness (r = 0.44)

(5) Tensile modulus (r = 0.42)

c. Composite of normal and adverse operating conditions

(1) Tensile strength (r = 0.51)

(2) Tensile work (r = 0.48)

(3) "Elastic" work (r = 0.48)

(4) Tensile stiffness (r = 0.38)

(5) Alcohol-benzene extractives (r = 0.38)

2. The simple correlation coefficients in (1) above were only of intermediate magnitude. Thus, none of the properties, taken individually, were highly related to high-low flute formation.

COMBINED DATA. NORMAL AND ADVERSE OPERATING CONDITIONS

3. Considering predictive accuracy, significance of individual properties, and multiple correlation coefficients, average flute height differences appeared to be best related to either of the following sets of properties:

a. Tensile strength and formation;

b. Tensile strength, formation, and hygroexpansivity contraction (92-25% R.H.).

4. The average predictive accuracies of 3-a and 3-b were 16.6 and 15.4%, respectively. Thus, inclusion of the hygroexpansivity contraction made only a small improvement in predictive accuracy. Also, it may be noted that the average prediction accuracies are fairly large. However, this is attributable in part to the high coefficients of variation associated with the flute height differences.

5. Average flute height differences increased as

a. tensile strength increased;

b. formation became less uniform;

c. the hygroexpansivity contraction increased.

6. An independent check of the regression equations was made employing data from another study (Project 2696-7, report in progress). While the data are not included in this study, the results indicated that the predictions of average flute height difference from tensile strength and formation were in reasonably good agreement with the observed values. This lends support to the conclusion that tensile strength and formation influence high-lows.

NORMAL CORRUGATING CONDITION DATA

7. The best predictions of average flute height differences with all properties significant at the 0.05 level or better were obtained with the following combinations of properties:

a. alcohol-benzene extractives;

b. formation;

c. friction.

The average prediction error was 13.2%.

8. In 7, average flute height differences increased as

a. alcohol-benzene extractives decreased;

b. formation became less uniform;

c. friction increased.

9. As an alternative to regression equations based on alcohol-benzene extractives as one of the properties, it appeared that the combination of tensile strength and formation gave the next best predictions of single-face flute height differences. The average predictive accuracy was 15.4%. The direction of the effects of tensile strength and formation was the same as in 5 above.

ADVERSE CORRUGATING CONDITIONS

10. Stepwise, multiple regression analysis indicated that some improvement in predictive accuracy — relative to tensile strength or tensile work alone — could be achieved with either of the following sets of properties:

a. tensile strength, hygroexpansivity contraction (92-25% R.H.), and caliper;

b. tensile work, hygroexpansivity (25-92% R.H.), and caliper.

However, in these regressions only tensile strength and tensile work were highly significant (0.01 level).

GENERAL

The above results suggest that high-lows are influenced by the tensile load-elongation characteristics of the medium. It is speculated that this may occur because the amount of strain recovery in the medium after passage through the corrugating nip will be dependent on the load-elongation characteristics of the medium. Formation uniformity may influence high-lows because of local differences in the response of the sheet to the corrugating stresses. Also, local differences in density and caliper may affect the oscillatory displacement of the upper roll and the consequent molding of the flute. Hygroexpansivity may influence high-lows due to stress and strain relaxation effects associated with the changes in moisture content of the medium during corrugating.

In addition to the above, the analysis also suggested that the kinetic coefficient of friction and the amount of alcohol-benzene extractives influence high-lows. The coefficient of friction may be expected to influence the tensions induced in the web in the corrugating labyrinth and consequently affect the amount of strain recovery after the corrugating nip. The alcohol-benzene extractives may be expected to contain various resins and waxes. While present in relatively small amounts, one or more of the constituents may affect the permanency of flute molding and/or the frictional characteristics of the medium.

INTRODUCTION

One limiting factor in the corrugating operation is the formation of high-low flutes. The tendency to form high-low corrugations has been shown to vary significantly from medium-to-medium and is also dependent on the corrugator operating conditions (1). However, there is little known relative to which properties of the corrugating medium influence high-low flute formation. With this in mind, this study was initiated for the purpose of investigating relationships between conventional and special corrugating medium properties and the occurrence of high-low corrugations.

A review of the literature relative to high-low flute formation may be found in Reference (1). In general, most of the writers — Velarde (2), Skiver (3), Scordas (4), and Wilson (5) — mention moisture content of the medium as a factor in causing high-lows. Wilson (5) also notes that fugitive rosins or sizes may cause the medium to stick to the corrugating rolls — perhaps contributing to high-low formation. Other than the above, there seems to be no information in the literature indicating specific properties of the medium causing high-lows.

In general, high-low corrugations are a manifestation of the fact that the heights of consecutive flutes vary in a periodic manner — i.e., the heights tend to be alternately high and low. The height periodicity appears to be present in all corrugated board regardless of medium even though the magnitude may differ from medium to medium. The fact that the phenomenon is invariably encountered indicates that the basic cause is inherent in the process though the magnitude may be influenced by the medium.

MATERIALS

Twenty-one 26-lb. semichemical mediums were selected from the medium base-line study so as to provide a wide geographic representation of the types of medium currently included in the base-line study. A listing of the rolls selected together with their runnabilities in the medium base-line study may be found in Table I.

TABLE I

SEMICHEMICAL CORRUGATING MEDIUMS
SELECTED FOR STUDY

	FKI Runnabilities	
Roll No.	Speed, f.p.m.	Tension, lb./in.
688	600	1.5
694	600	1.5
708	600	1.5
710	600	1
714	600	1.5
717	600	1
718	600	1.5
722	600	1.5
728	600	1
732	600	1.5
762	600	1.5
733	600	Min.
768	600	1.5
723	600	1
746	600	1.5
793	600	1.5
779	600	1.5
751	600	1.5
802	600	1.5
790	600	0.5
831	600	1.5

FABRICATION

The selected mediums were fabricated into A-flute single-faced board on the Institute's corrugator using (a) normal operating conditions, and (b) adverse operating conditions known to produce more pronounced high-lows. Samples of the single-faced board were taken at speeds of 300 and 450 ft./min. for each condition.

The operating conditions were as follows:

A. Normal Operating Conditions

1. Tension: 0.5 lb./in.
2. Roll pressure: 327 lb./in.
3. Shower pressure: 14 p.s.i.
4. Angle of take-off: tangential

B. Adverse Operating Conditions

1. Tension: 2 lb./in.*
2. Roll pressure: 187 lb./in.
3. Shower pressure: none
4. Angle of take-off: 15° above tangential

*For many of the mediums it was necessary to reduce the web tension in the "adverse condition runs" to avoid flute fracture. The tensions used in these cases were as follows:

Roll No.	Tension, lb./in. 300 f.p.m.	450 f.p.m.
710	1.5	0.75
714	2	1.5
717	1	1
718	1	1
728	2	1.5
733	1	1
768	1	1
723	0.5	0.5
746	1.5	1.5
793	1	1
779	1.5	1.5
751	1.5	1.5
802	1.5	1.5
790	2.0	1.5

CONDITIONING

All materials were preconditioned for at least 24 hours at less than 35% R.H. and 73°F. and conditioned for at least 48 hours at 50% R.H. and 73°F. prior to test except when specifically noted in the test procedure.

TESTING PROCEDURES

SINGLE-FACED BOARD

From each sample of single-faced board, twenty 5-square inch circular specimens were cut at approximately 5-foot intervals avoiding folds and creases. A special caliper was used to measure the heights of five consecutive flutes on each specimen to the nearest 0.0001 inch. The force on the spindle of the dial gage was 100 grams and the diameter of the caliper foot was 3/8 inch.

The average individual flute caliper was calculated from the average of the 100 height measurements. The average difference in height of consecutive flutes (average flute height difference) was calculated by taking the absolute difference between consecutive flutes (four differences per five flute height measurements on a given specimen), summing the differences for the twenty specimens and dividing by the total number of differences — in this case, eighty.

In addition, the number of differences in height of consecutive flutes which fell in various ranges — e.g., 0-3.0, 0-4.0 points, etc., was counted to describe the distribution of differences.

CORRUGATING MEDIUM

Samples of each corrugating medium were taken at start and end of the fabrication runs. For each test property evaluated, half the determinations were made on the "start" sample and half were made on the "end" sample.

The properties evaluated are listed in Table II. In general, TAPPI standards were employed in the testing where possible. Test procedures for properties not covered by TAPPI standards are described briefly below.

TABLE II

TESTS ON CORRUGATING MEDIUM

		No. of Determinations
1.	Moisture content[a]	4
2.	Caliper	10
3.	Water drop[b]	10(5 felt; 5 wire side)
4.	Kinetic coefficient of friction	6(3 felt; 3 wire side)
5.	Tensile load-deformation curve[c]	5(M.D. only)
6.	Transverse compression	6
7.	Alcohol-benzene extracts	2
8.	Formation (Thwing-Albert)	4
9.	Hygroexpansivity	
	(a) 25-92% R.H.	2
	(b) 92-25% R.H.	2
10.	Concora moldability	10
11.	Concora caliper difference	35

[a]At time of fabrication

[b]At time of fabrication and at 50% R.H.

[c]The following properties were computed
(1) tensile
(2) stretch
(3) recoverable stretch
(4) nonrecoverable stretch
(5) tensile modulus (E)
(6) tensile stiffness, (Et), [modulus x thickness (t)]
(7) tensile work (tensile x stretch product)
(8) "elastic" work (tensile x recoverable stretch product)
(9) secant modulus

1. Kinetic coefficient of friction. The frictional properties of the medium (medium vs. chrome-plated steel) were determined using a modified form of the

tester described in Reference (6). A test was performed by placing a strip of medium on a Teflon-covered plane, placing a chrome-plated steel block (weight of block corresponded to 0.68 p.s.i. pressure on the specimen) on the top surface of the specimen and pulling the specimen from under the chromed block at a fixed rate of speed (87 in./min.). The chromed block was attached by means of a flexible cable to a cantilever beam which measured the frictional force.

2. Transverse compression. The transverse compression characteristics of the medium were measured by using a special compression jig to apply compressive force in the thickness direction of the sheet over an effective specimen area of 0.25 square inch. Load-deformation curves were obtained using a test rate of 3,000 lb./min. The change in caliper expressed as a percentage of the original caliper was determined at pressures of 2000 and 5000 p.s.i. and the "permanent" change in caliper in percent after removal of the 5000 p.s.i. pressure was calculated.

3. Tensile load-deformation curves. Machine direction tensile load-elongation curves were obtained using a span of 180 mm. and a test rate of 60 lb./min. From the load-elongation curves the ultimate tensile and stretch values were obtained and the tensile modulus (E) and tensile stiffness, Et, were calculated from the initial slope (see Fig. 1). In addition, estimates of the recoverable and nonrecoverable stretch were derived from the curves as illustrated in Fig. 1. Approximate measures of energy absorption capacity were obtained by calculating the following quantities — (1) tensile x stretch, and (2) tensile x recoverable stretch. They were termed tensile work and "elastic" work, respectively. The secant modulus was calculated from the slope of the line extending from the origin through the point corresponding to the maximum tensile and stretch (see Fig. 1).

4. Concora caliper difference. Five specimens were fluted on the Concora fluter, taped and conditioned for 30 minutes after taping in the 50% R.H. atmosphere.

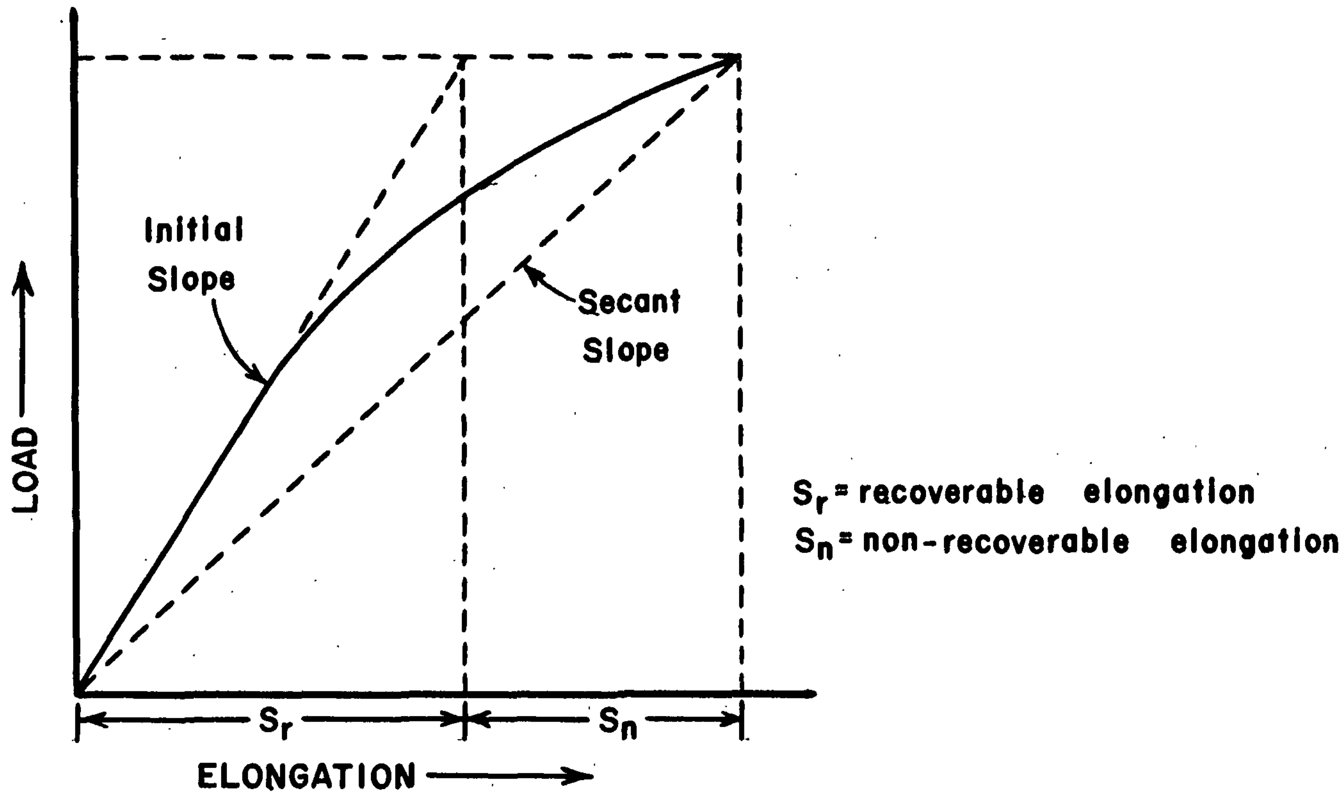

Figure 1. Tensile Load-Elongation Curve Properties

The heights of the ten flutes on each specimen were then measured using the same caliper used for the single-faced board caliper measurements. The differences in height between adjacent flutes were calculated using the results for the middle eight flutes (Note: The results for the two end flutes were not used in the calculations because they tended to exhibit greater heights than the middle eight flutes). Thus, seven height differences were obtained for each specimen giving 35 differences for the five specimens. The average flute height difference was recorded to the nearest 0.1 point.

5. Concora moldability length. This procedure was investigated for the purpose of determining if the various mediums exhibited differences in "spring back" after corrugating in the Concora fluter. Briefly, specimens were fluted in the Concora fluter and the specimen was placed on a flat surface. A glass microscope slide, 1 x 3 inches in size and weighing 5.7 g., was laid on top of the specimen. The length of the specimen was then measured after allowing it to relax for periods of 10 and 60 seconds. A steel rule graduated in 0.01-inch increments was used. The lengths after 60 seconds relaxation were averaged for the ten specimens tested for each sample. It should be remarked that while differences were found between mediums, the differences were relatively small considering the possible errors in measurement.

DISCUSSION OF RESULTS

FLUTE HEIGHT DIFFERENCES — SINGLE-FACED BOARD

As mentioned previously, twenty-one 26-lb. semichemical mediums were fabricated into single-faced board using (a) normal operating conditions which generally result in a minimum of high-lows, and (b) adverse operating conditions which generally result in a greater tendency to high-low flute formation. Flute height measurements were made on single-faced board samples taken at 300 and 450 f.p.m. at each condition. The differences in height between consecutive flutes were calculated and the average flute height differences (based on 80 difference measurements at each speed) are summarized in Table III for each sample roll. More detailed summaries of the flute height data may be found in Appendix I.

When the flute height differences are averaged for the two speeds, it may be noted in Table III or Fig. 2 that the results at normal corrugating conditions ranged from a low of 1.06 points for Roll 688 to a high of 2.60 points for Roll 710. Under adverse conditions the flute height differences averaged for the two speeds ranged from a low of 1.82 points for Roll 717 to a high of 4.68 points for Roll 768. Thus, the mediums selected for the study exhibited a fairly wide range of flute height differences.

It may be noted that the adverse operating conditions generally resulted in greater average flute height differences relative to the normal operating conditions. Thus, the overall average flute height difference of 1.71 points for normal operating conditions increased to 3.08 points for the adverse operating conditions. Therefore, operating conditions do influence high-lows as experience and past studies have shown.

TABLE III

SUMMARY OF AVERAGE FLUTE HEIGHT DIFFERENCES ON SINGLE-FACED BOARD

Roll No.	Normal Corrugating Conditions: Flute Ht. Diff., pt. 300 f.p.m.	450 f.p.m.	Av.	Normal: Percent Less than 4.0 pt. 300 f.p.m.	450 f.p.m.	Av.	Adverse Corrugating Conditions: Flute Ht. Diff., pt. 300 f.p.m.	450 f.p.m.	Av.	Adverse: Percent Less than 4.0 pt. 300 f.p.m.	450 f.p.m.	Av.	Composite: Flute Ht. Diff., pt.	Composite: Percent Less than 4.0 pt.
688	1.06	1.07	1.06	100.0	100.0	100.0	2.50	2.18	2.34	81.2	85.0	83.1	1.70	91.6
694	1.39	1.86	1.62	100.0	93.8	96.9	1.96	2.71	2.34	93.8	82.5	88.2	1.98	92.6
708	1.29	0.91	1.10	96.2	100.0	98.1	2.16	2.83	2.50	86.2	75.0	80.6	1.80	89.4
710	2.03	3.17	2.60	87.5	66.2	76.8	4.05	5.08	4.56	57.5	42.5	50.0	3.58	63.4
714	1.82	1.90	1.86	95.0	93.8	94.4	3.28	3.50	3.39	68.7	63.7	66.2	2.62	80.3
717	1.60	1.63	1.62	93.8	97.5	95.6	1.87	1.77	1.82	92.5	92.5	92.5	1.72	94.0
718	1.28	1.61	1.44	100.0	95.0	97.5	2.02	2.43	2.22	91.2	85.0	88.1	1.83	92.8
722	1.95	2.44	2.20	95.0	78.7	86.8	4.14	2.85	3.50	57.5	80.0	68.8	2.85	77.8
728	1.35	1.37	1.36	100.0	98.7	99.4	2.40	2.93	2.66	82.2	75.0	78.6	2.01	89.0
732	2.07	1.98	2.02	95.0	95.0	95.0	3.46	4.13	3.80	67.5	51.2	59.4	2.91	77.2
762	1.37	1.58	1.48	100.0	100.0	100.0	2.38	3.43	2.90	85.0	61.2	73.1	2.19	86.6
733	1.82	2.53	2.18	87.5	81.2	84.4	3.24	3.21	3.22	65.0	66.2	65.6	2.70	75.0
768	2.51	2.30	2.40	80.0	80.0	80.0	3.65	5.71	4.68	63.7	42.5	53.1	3.54	66.6
723	1.65	1.94	1.80	95.0	93.8	94.4	3.67	4.97	4.32	60.0	47.5	53.8	3.06	74.1
746	1.41	1.55	1.48	98.7	96.2	97.4	2.97	3.47	3.22	71.2	60.0	65.6	2.35	81.5
793	1.70	1.36	1.53	95.0	100.0	97.5	2.74	2.58	2.66	72.5	82.5	77.5	2.10	87.5
779	1.31	1.59	1.45	100.0	95.0	97.5	2.86	3.53	3.20	75.0	63.7	69.4	2.32	83.4
751	1.58	1.72	1.65	96.2	92.5	94.4	1.91	2.84	2.38	92.5	70.0	81.2	2.02	87.8
802	1.39	1.57	1.48	98.7	97.5	98.1	2.02	2.55	2.28	83.7	81.2	82.4	1.88	90.2
790	1.59	1.61	1.60	95.0	95.0	95.0	3.28	3.07	3.18	68.7	72.5	70.6	2.39	82.8
831	1.92	2.16	2.04	92.5	85.0	88.8	3.23	3.87	3.55	66.2	61.2	63.7	2.80	76.2
Overall average	1.62	1.80	1.71	95.3	92.1	93.7	2.85	3.32	3.08	75.3	68.6	72.0	2.40	82.8

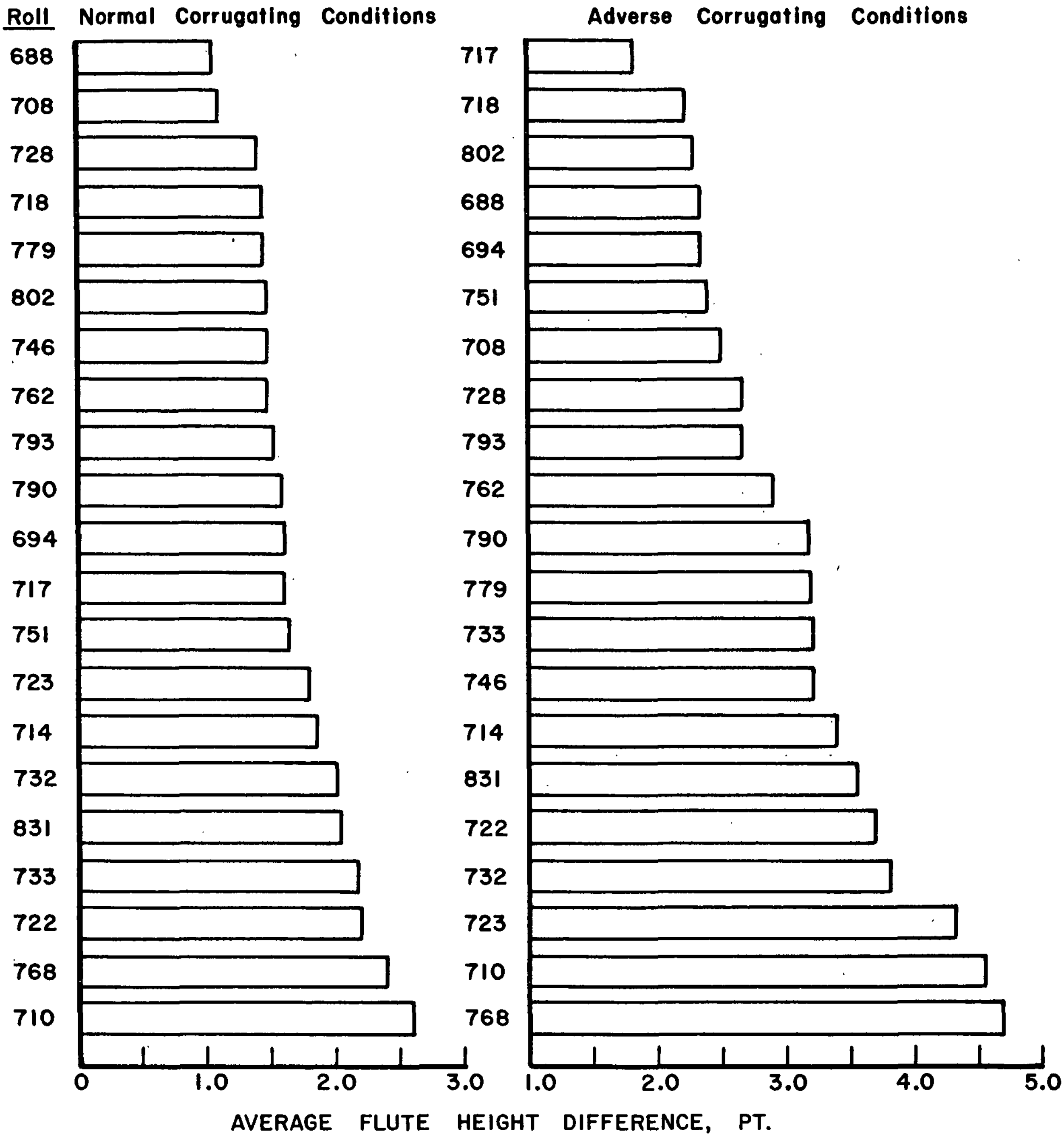

Figure 2. Average Flute Height Differences for Single-Faced Board

In assessing the significance of differences between rolls with regard to average flute height difference, Reference (2) indicated the coefficient of variation for caliper differences was relatively high — about 73%. The standard deviations obtained in this study (see Appendix I) also would result in similar magnitudes for the coefficient of variation. Thus, the precision of the average flute height difference is relatively low.

A current study (Project 2696-7) indicates that the standard error of an average of 80 observations will be approximately 0.3 point. This is a composite estimate involving both the variability of individual observations and between-run variability. Thus, confidence limits on the average flute height differences at each speed would be approximately ± 0.6 point. For the averages of the results at two speeds the standard error would be approximately 0.23 point and the approximate 95% confidence limits would be ± 0.46 point. Despite the large number of observations involved, the confidence limits are relatively broad and this fact must be taken into account when assessing differences between rolls or the prediction errors discussed in later pages.

It should be kept in mind that the individual flute height difference observations do not conform to the "normal distribution" curve because the sign of the observation is disregarded. This results in skewed distributions. Therefore, "normal distribution" curve statistics cannot be used to make accurate statements relative to the distribution of the individual observations. This fact should be kept in mind in interpreting the standard deviations shown in Appendix I.

High-low corrugations become evident at the double-backer when the flute height differences exceed several points — say 4 or 5 points. Because the flute height differences observations are not normally distributed, it is not possible to readily relate average flute height differences to the number of larger differences present. For this reason the percentage of individual differences falling below several arbitrarily selected values was determined. Table III tabulates these results for an endpoint of 4.0 points; Appendix I gives results for 3.0 and 5.0-point endpoints. Which, if any, of the above endpoints may have the most practical value is not clearly evident. However, it has been suggested that high-lows can be discerned when differences are greater than 4 to 5 points.

Taking the 4.0-point endpoint, the maximum and minimum average flute height differences are related to the percentage of differences less than 4.0 points as follows:

	Av. Flute Ht. Diff., points	Percent Less Than 4.0 Points
Normal operation		
Roll 688	1.06	100.0
Roll 710	2.60	76.8
Adverse operation		
Roll 717	1.82	92.5
Roll 768	4.68	53.1

It may be seen that for the higher average flute height differences substantial percentages of the individual flute height differences exceed 4.0 points.

The above results can be generalized as shown in Fig. 3. In the figure, the average flute height difference is plotted against the cumulative distribution values for the 3.0 and 4.0-point endpoints. Relatively smooth curvilinear relationships were obtained. Thus, average flute height differences can be interpreted in terms of the number of larger differences present. It may be noted that neither curve passes through the 50% level at the endpoint. This reflects the skewed nature of the distributions.

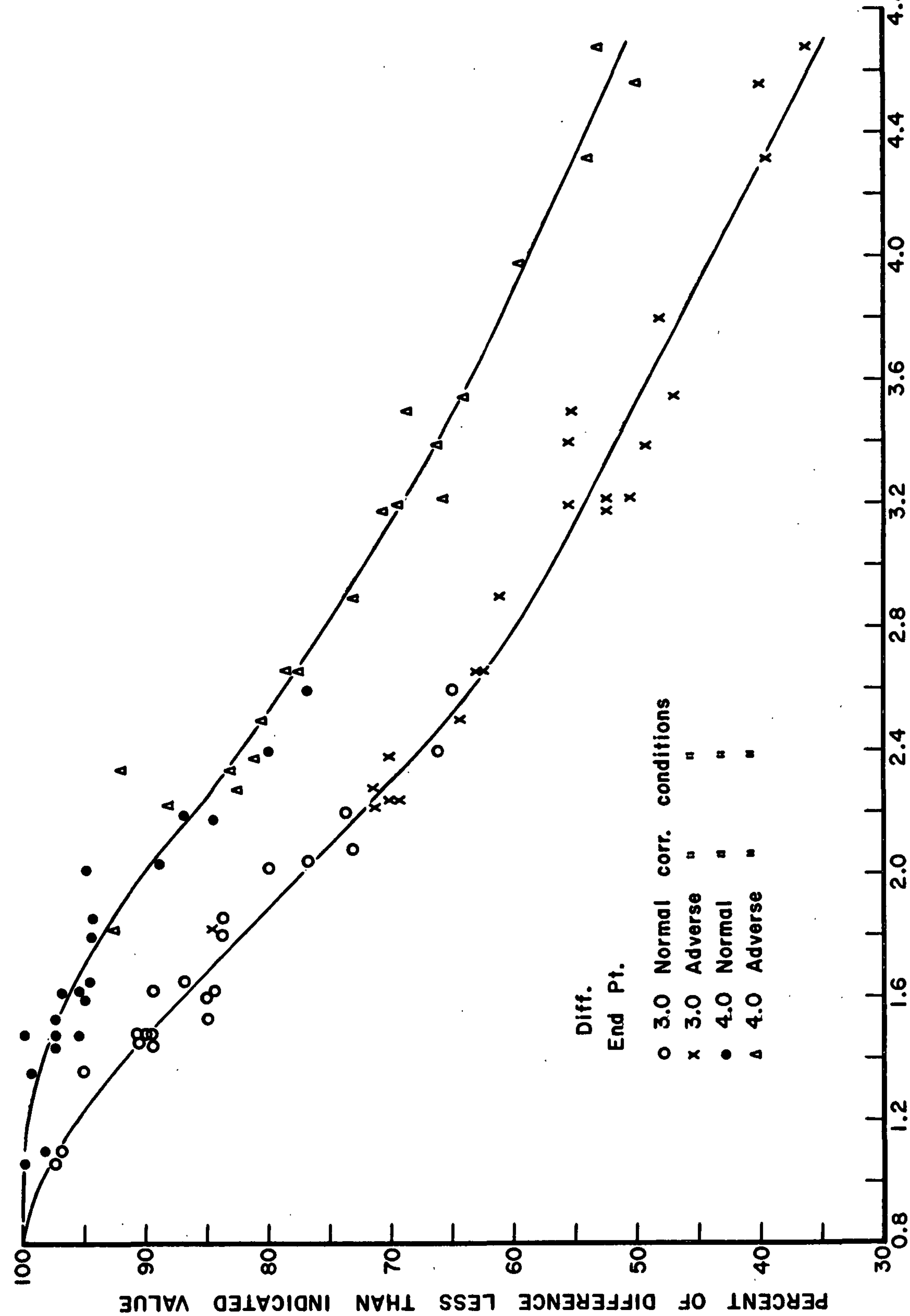

Figure 3. Relationship Between Average Flute Height Differences and Percentage of Individual Differences less than 3.0 and 4.0 Points

A scatter diagram illustrating the relationship between the results obtained under normal and adverse operating conditions is shown in Fig. 4. A correlation coefficient of 0.763 was obtained. Thus, the flute height differences under normal conditions were fairly well related to the caliper differences under adverse operating conditions. The relationship is not perfect and this may reflect, in part, the relatively high variability of the high-low measurements.

PHYSICAL PROPERTIES OF CORRUGATING MEDIUM

The properties of the corrugating medium which were evaluated in this study are tabulated in Table IV. It may be noted that the alcohol-benzene extractives were determined for each medium sample because initial exploratory results suggested that the percentage of extractives might be related to high-low flute formation.

From one standpoint high-lows may be regarded as a response to the machine direction tensile stresses and strains imposed in the corrugating operation. For this reason, the tensile load-elongation curves were analyzed to derive approximate estimates for both recoverable and nonrecoverable stretch (see Fig. 1). At a later period in the analysis it was thought that the tensile energy absorption characteristics of the medium should also be evaluated.

In the interest of economy and time the area under the tensile load-elongation curve was not measured to directly determine the tensile energy absorption capacity. Instead, the product of tensile strength times total stretch was calculated and termed tensile work in this report. Tensile work determined in this matter is related but not equal to tensile energy absorption. However, as long as the tensile load-elongation curve shapes are not too dissimilar, it may be expected there will be a fair correlation between tensile work and tensile energy absorption (7). In this regard Burgstaller and Krause followed essentially this procedure in their work on

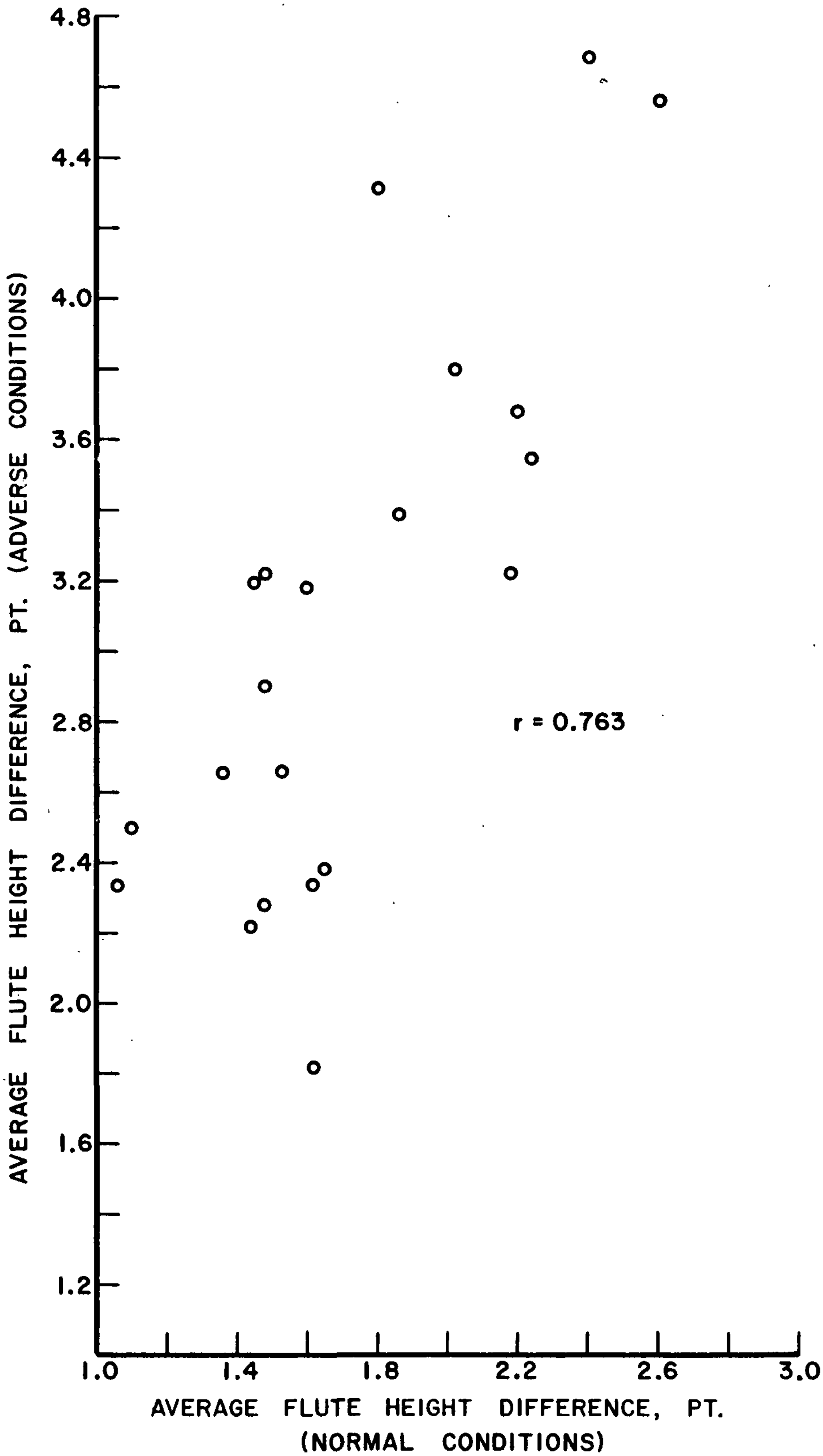

Figure 4. Correlation Between Average Flute Height Differences for Normal and Adverse Corrugating Conditions

TABLE IV

CORRUGATING MEDIUM PROPERTIES

Roll No.	Moisture, % o.d.[a]	Caliper, pt.	Transverse Compression, % 2000 p.s.i.	5000 p.s.i.	"Permanent"	Coeff. of Friction	Water Drop, sec.	Formation, units	Alcohol-Benzene Ext., %	Hygroexpansivity, % 25-92%	92-25%
688	7.0	11.0	45.1	59.8	44.8	0.30	176.5	10.0	2.68	0.363	-0.538
694	4.2	10.6	40.5	56.1	39.9	0.28	37.0	7.76	1.02	0.240	-0.489
708	5.8	9.9	39.7	54.5	38.6	0.30	62.3	11.8	3.34	0.356	-0.583
710	6.4	10.3	41.0	54.9	38.9	0.27	42.6	7.56	0.48	0.276	-0.468
714	5.7	9.6	36.3	52.0	35.4	0.25	70.1	8.49	1.62	0.255	-0.756
717	3.5	10.9	44.4	59.8	45.5	0.25	21.2	9.80	1.12	0.388	-0.799
718	3.4	12.0	48.9	61.6	48.1	0.25	17.0	13.4	1.26	0.354	-0.623
722	9.4	11.0	46.0	60.6	46.2	0.27	52.9	7.84	0.80	0.416	-0.552
728	6.0	10.0	41.8	56.6	38.9	0.24	42.5	14.8	0.90	0.186	-0.376
732	3.4	10.2	43.7	57.6	42.4	0.26	60.3	12.4	0.64	0.256	-0.452
762	4.0	10.3	44.5	59.6	43.3	0.23	262.9	9.05	0.86	0.248	-0.450
733	5.0	11.7	42.6	58.4	42.9	0.26	127.0	9.55	0.90	0.363	-0.522
768	3.6	10.3	41.8	56.8	41.6	0.28	86.8	7.55	1.38	0.393	-0.711
723	4.2	10.2	43.3	57.8	41.5	0.22	54.2	10.3	0.86	0.298	-0.527
746	3.6	10.9	45.5	60.2	43.3	0.24	108.8	10.5	1.87	0.323	-0.534
793	3.2	11.4	46.9	61.2	44.3	0.27	16.0	11.4	0.50	0.268	-0.566
779	5.8	10.8	42.3	57.9	41.3	0.24	80.1	11.8	0.49	0.348	-0.602
751	3.2	11.4	45.1	60.6	45.0	0.24	95.4	9.95	0.79	0.306	-0.556
802	2.6	10.2	39.5	54.9	38.0	0.22	245.8	8.00	0.99	0.264	-0.518
790	6.1	10.2	42.0	55.5	39.2	0.22	56.0	7.00	1.44	0.327	-0.522
831	11.3	11.1	52.8	64.6	49.3	0.27	223.9	11.1	0.54	0.400	-0.572

Roll No.	Concora Tests Caliper Diff., pt.	Moldability, in.	Tensile (T), lb./in.	Stretch, % Total (S_t)	Recoverable (S_r)	Nonrecoverable (S_n)	Tensile Modulus, p.s.i.x10^3	Tensile Stiffness, lb./in.	Secant Modulus, p.s.i.x10^3	Tensile work, in.lb./in.^{2}x10^2	Elastic work, in.lb./in.^{2}x10^2
688	1.71	3.86	38.2	1.65	0.85	0.80	409	4500	210	63.0	32.5
694	2.14	3.94	40.6	1.21	0.73	0.48	525	5560	317	49.1	29.6
708	1.46	3.88	32.0	1.09	0.69	0.40	467	4620	297	34.9	22.1
710	1.43	3.98	53.9	1.65	0.86	0.79	612	6300	317	88.9	46.4
714	1.91	3.88	36.0	1.35	0.75	0.60	502	4820	278	48.6	27.0
717	2.04	3.86	30.4	1.62	0.83	0.79	335	3650	172	49.2	25.2
718	1.71	3.89	37.7	1.20	0.70	0.50	450	5400	262	45.2	26.4
722	1.81	3.86	45.7	1.66	0.85	0.81	491	5400	250	75.9	38.8
728	2.21	4.00	45.2	1.04	0.68	0.36	660	6600	435	47.0	30.7
732	2.08	3.97	54.9	1.73	0.87	0.86	618	6300	311	95.0	47.8
762	1.75	3.99	39.8	1.18	0.76	0.42	510	5250	327	47.0	30.2
733	1.62	3.97	39.7	1.51	0.88	0.63	385	4500	225	59.9	34.9
768	2.16	3.94	36.5	1.37	0.71	0.66	496	5110	259	50.0	25.9
723	2.11	3.92	46.2	1.76	0.83	0.93	484	5570	257	81.3	38.3
746	1.70	3.96	39.8	1.34	0.80	0.54	456	4970	272	53.3	31.8
793	1.26	4.01	46.4	1.76	0.88	0.88	461	5260	231	81.7	40.8
779	1.99	3.91	46.1	1.48	0.75	0.73	571	6170	288	68.2	34.6
751	1.70	3.97	41.9	1.78	0.93	0.85	395	4500	206	74.6	39.0
802	1.91	3.97	37.8	1.18	0.71	0.47	520	5300	314	44.6	26.8
790	2.00	3.91	47.7	1.64	0.87	0.77	535	5460	285	78.2	41.5
831	1.65	3.90	42.3	1.20	0.80	0.40	478	5310	318	50.8	33.8

[a]At time of fabrication.

sack performance (8, 9). The product of tensile strength times recoverable stretch was also calculated and termed "elastic" work. This quantity might be expected to be approximately related to the elastic energy absorption characteristics of the medium. While the above are approximations it was believed they would serve to indicate whether energy absorption characteristics were better related to high-lows than other tension properties.

SIMPLE CORRELATIONS

The simple correlation coefficients between the average flute height differences of the single-faced board and the various medium properties are listed in Table V. Figure 5 illustrates the degree of correlation for each medium property. Scatter diagrams illustrating the relationship of each individual property to the average flute height differences are shown in Fig. 6-25.

Normal Corrugating Conditions

For normal corrugating conditions the following properties gave simple correlation coefficients which were statistically significant at the 0.10 or 0.05 levels.

1. Alcohol-benzene extracts $r = -0.53$
2. Formation $r = -0.44$
3. "Elastic" work $r = 0.44$
4. Tensile work $r = 0.42$
5. Tensile strength $r = 0.40$

Thus, flute height differences tend to increase as (a) the amount of extractives decrease, (b) the formation becomes poorer (lower), and (c) the tensile strength, tensile work and "elastic" tensile work increase.

TABLE V

CORRELATION BETWEEN VARIOUS PROPERTIES OF
THE MEDIUM AND AVERAGE FLUTE HEIGHT DIFFERENCES

		Correlation Coefficient		
No.	Property	Normal Corrugating Conditions	Adverse Corrugating Conditions	Composite
1	Moisture	0.21	0.24	0.25
2.	Caliper (t)	-0.01	-0.32	-0.22
3.	Concora caliper difference	0.03	0.10	0.08
4.	Concora moldability	0.15	0.15	0.16
5.	Transverse compression	0.02	-0.17	-0.11
6.	Friction	0.07	0.01	0.03
7.	Water drop	-0.12	-0.06	-0.08
8.	Tensile (T)	0.40[b]	0.52[a]	0.51[a]
9.	Stretch (S)	0.31	0.26	0.29
10.	Recoverable stretch (S_r)	0.31	0.15	0.22
11.	Nonrecoverable stretch	0.29	0.30	0.31
12.	Tensile modulus (E)	0.17	0.42[b]	0.35
13.	Tensile stiffness (Et)	0.21	0.44[a]	0.38[b]
14.	Secant modulus	-0.04	0.17	0.10
15.	Tensile work (T x S)	0.42[b]	0.47[a]	0.48[a]
16.	"Elastic" work (T x S_r)	0.44[a]	0.46[a]	0.48[a]
17.	Formation	-0.44[a]	-0.28	-0.35
18.	Alcohol-benzene extracts	-0.53[a]	-0.28	-0.38[b]
19.	Hygroexpansivity, 25-92% R.H.	0.18	0.08	0.12
20.	Hygroexpansivity, 92-25% R.H.	-0.08	0.08	0.03
21.	Hygroexpansivity, difference	-0.07	-0.16	-0.13

[a]Significant at the 0.05 level (0.433).

[b]Significant at the 0.10 level (0.369).

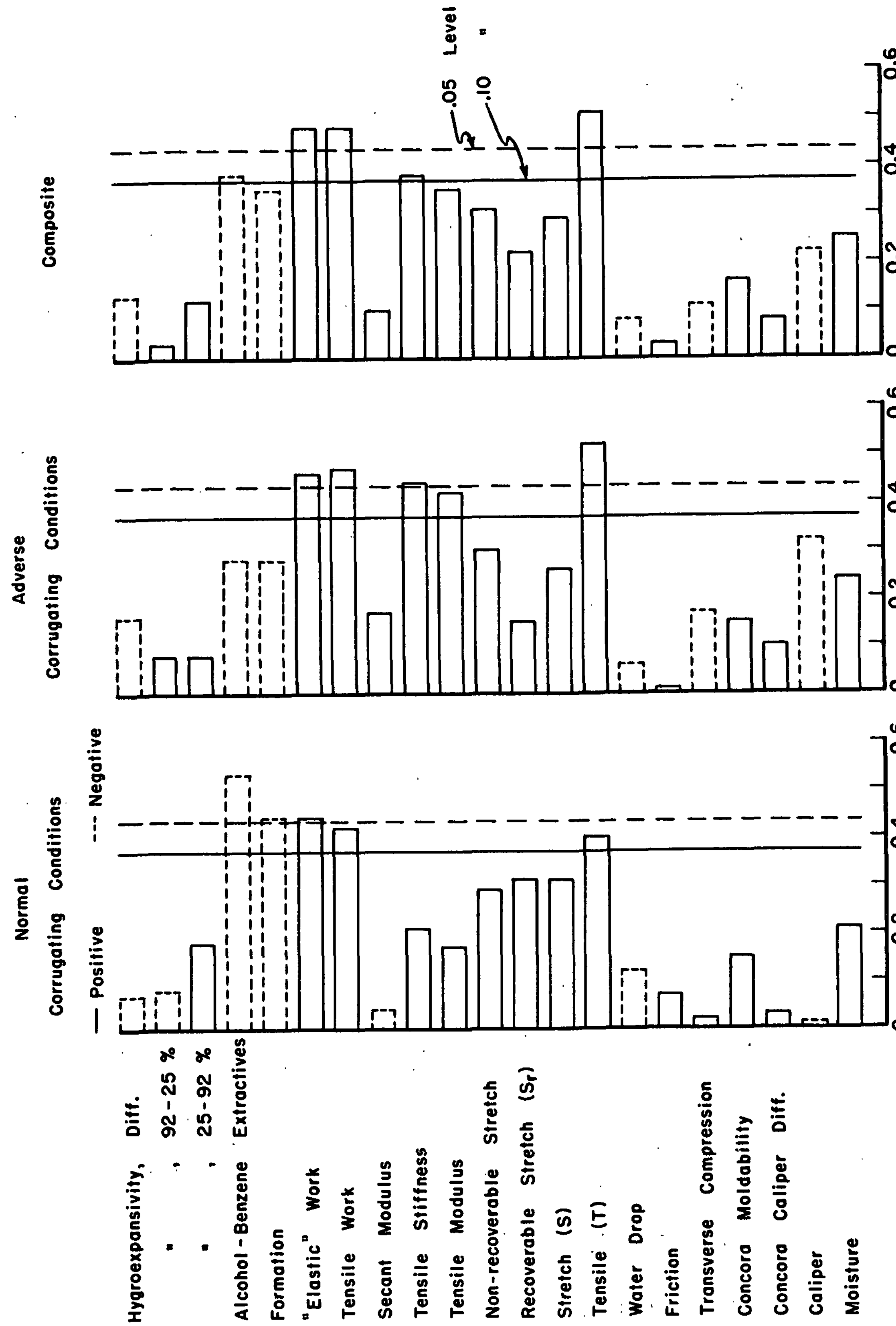

Figure 5. Correlation Between Medium Properties and Average Flute Height Differences on Single-Faced Board

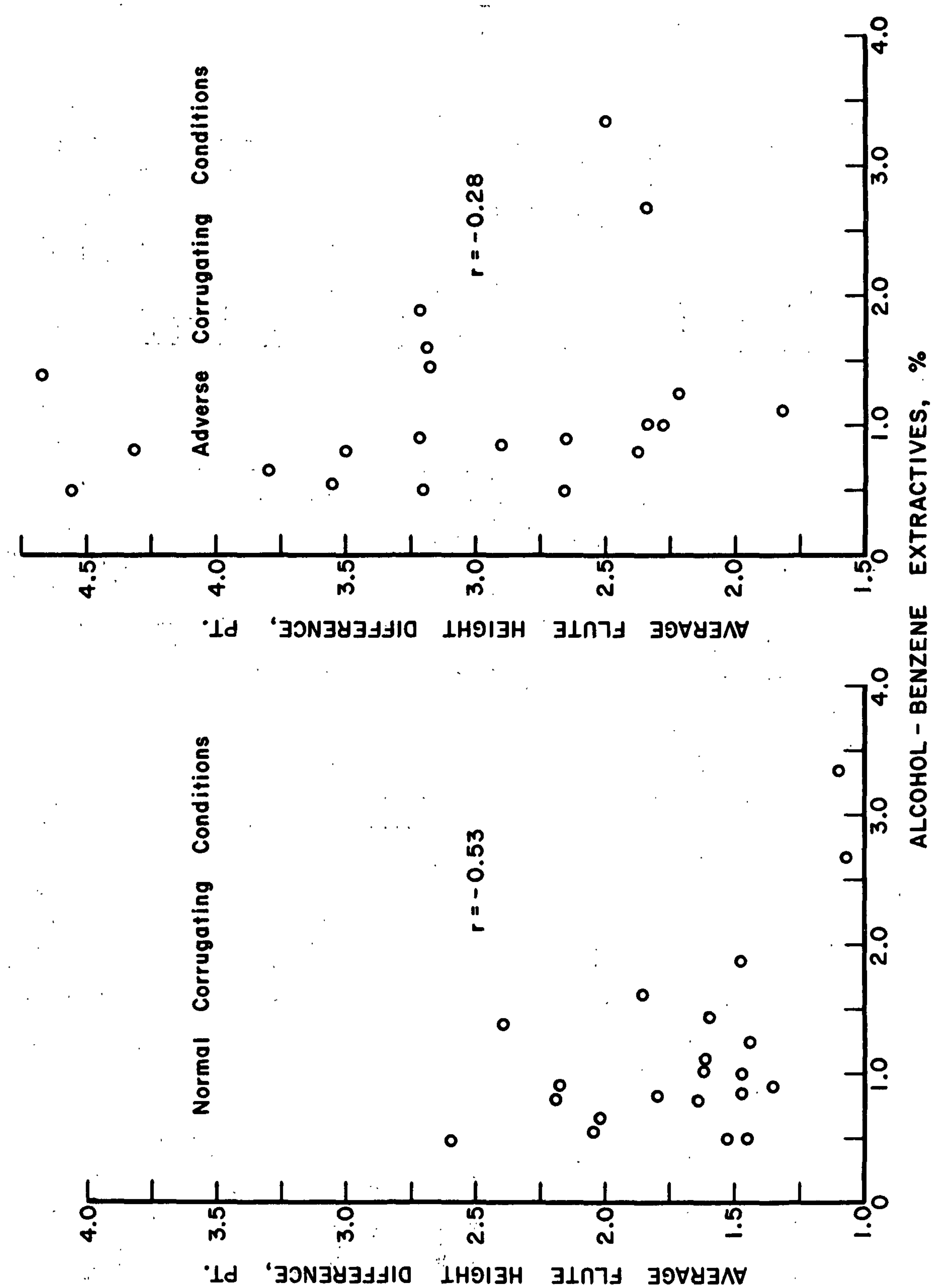

Figure 6. Relationship Between Alcohol-Benzene Extractives and Average Flute Height Difference

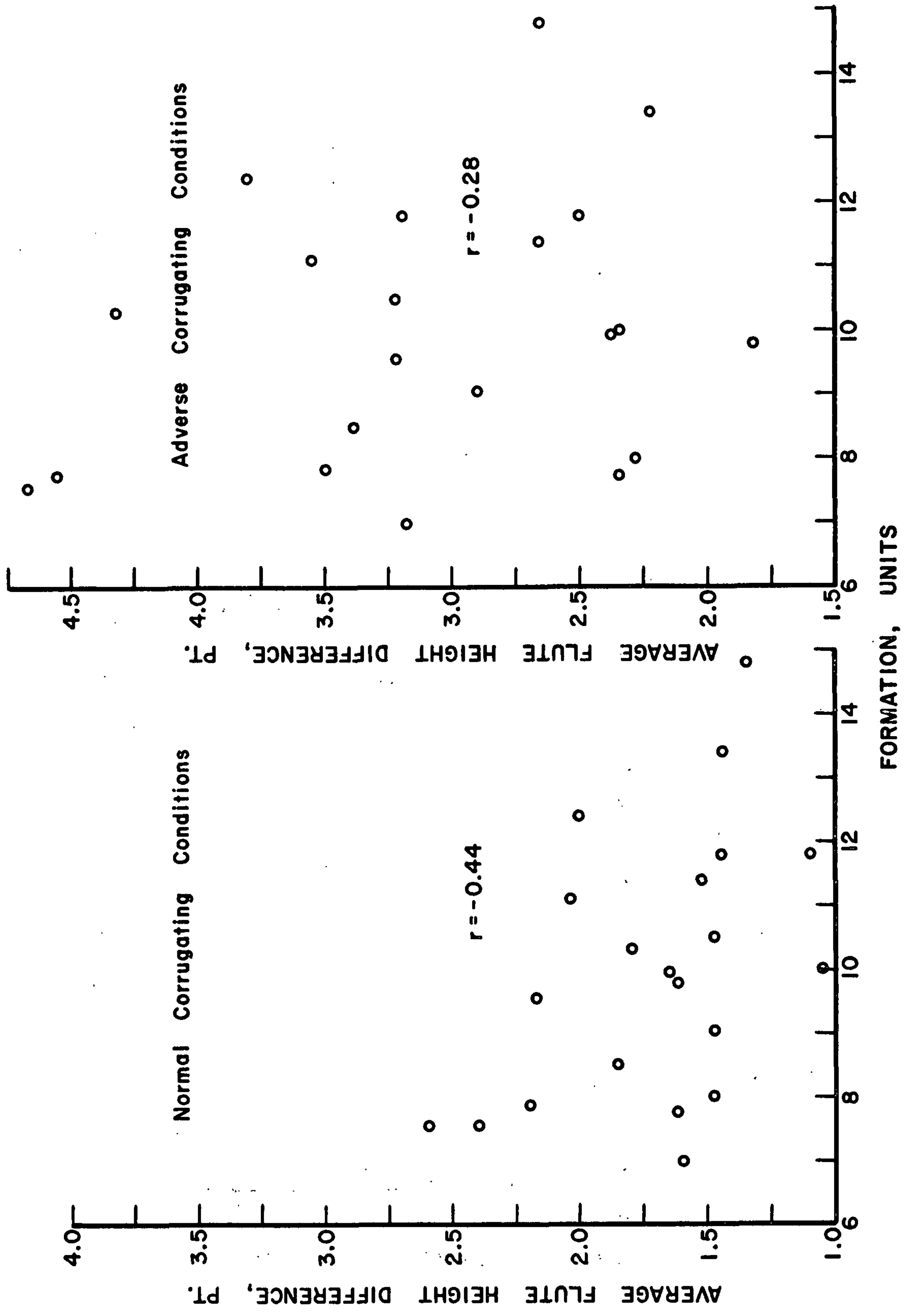

Figure 7. Relationship Between Formation and Average Flute Height Difference

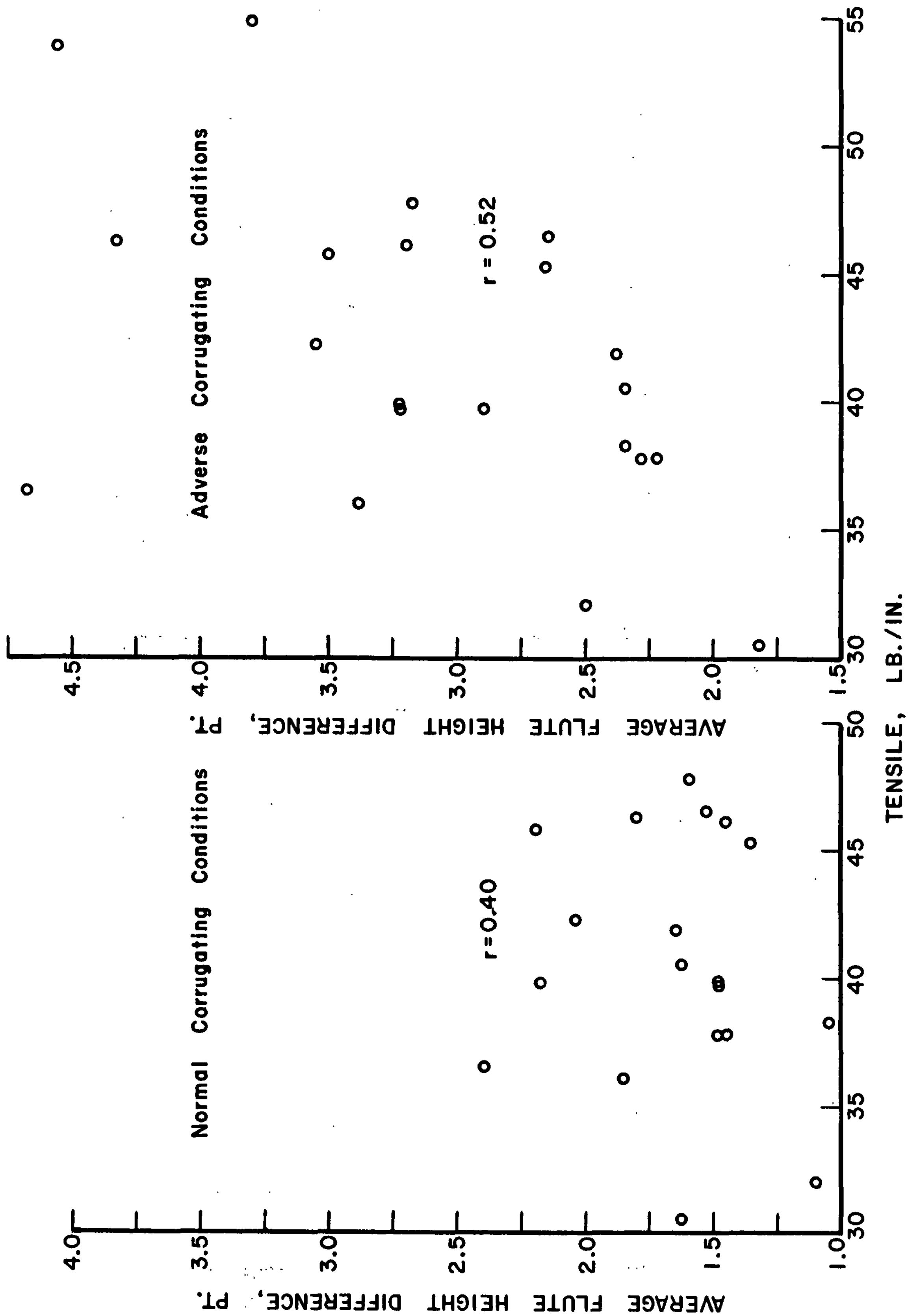

Figure 8. Relationship Between Tensile Strength and Average Flute Height Difference

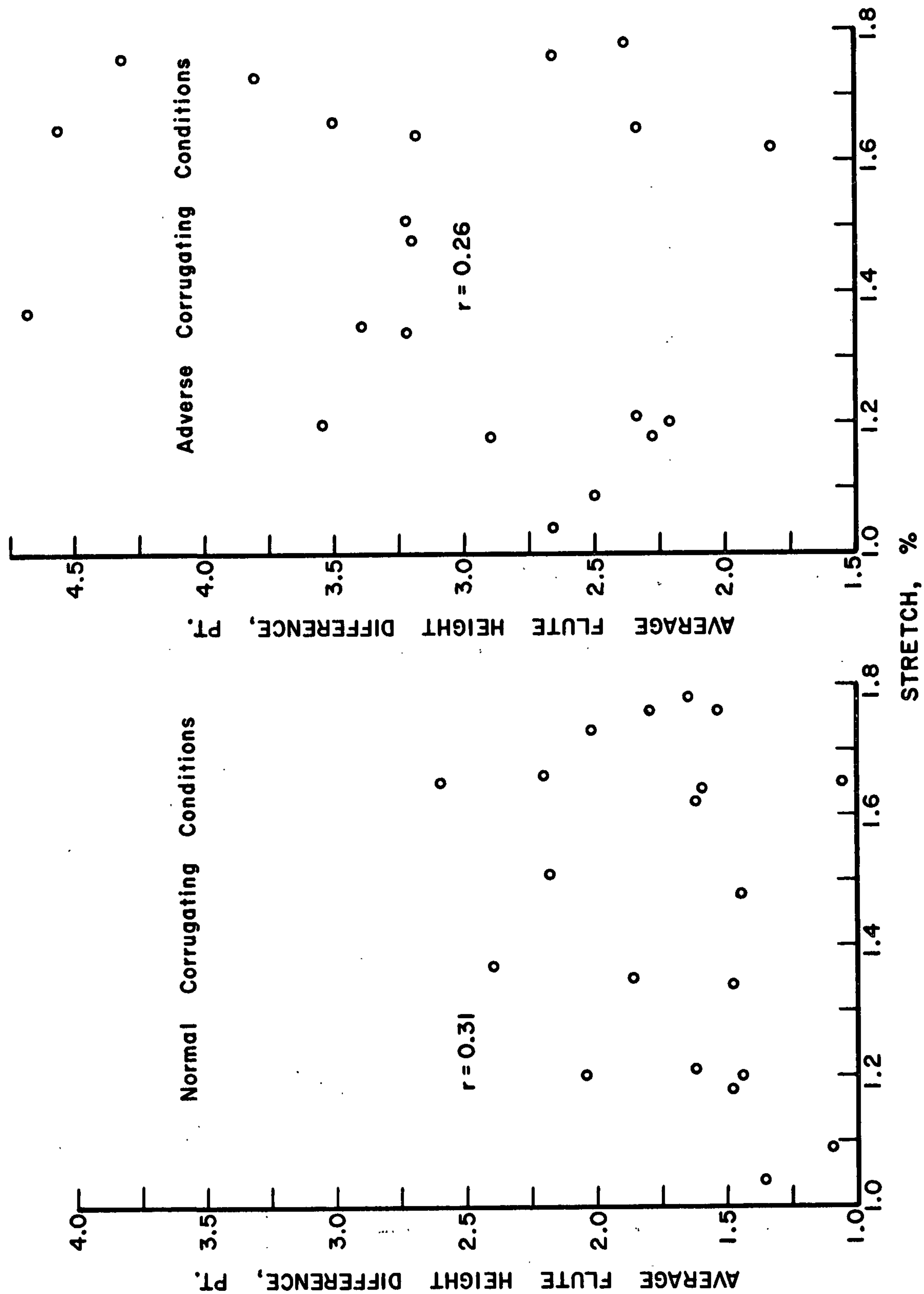

Figure 9. Relationship Between Stretch and Average Flute Height Difference

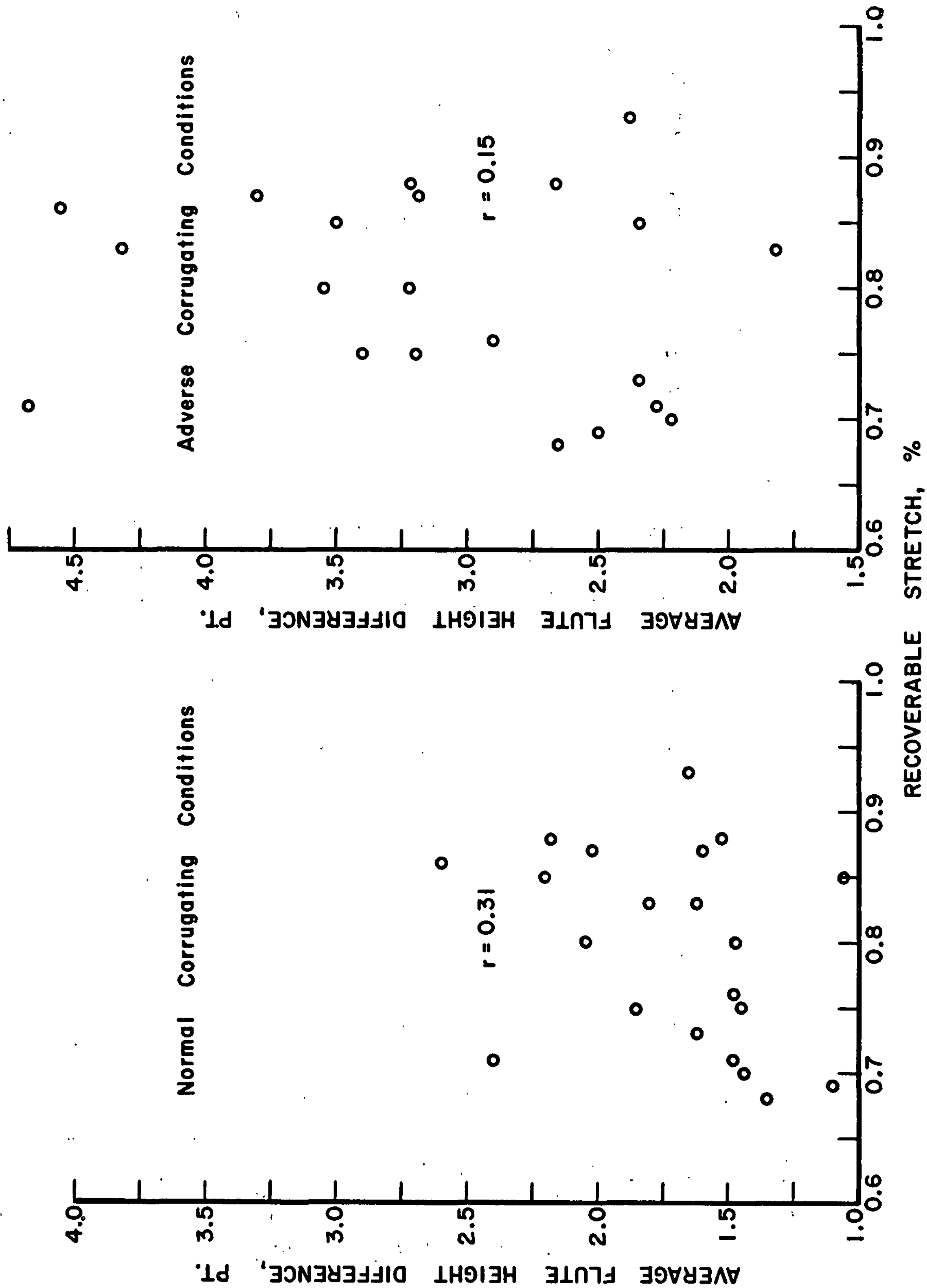

Figure 10. Relationship Between Recoverable Stretch and Average Flute Height Difference

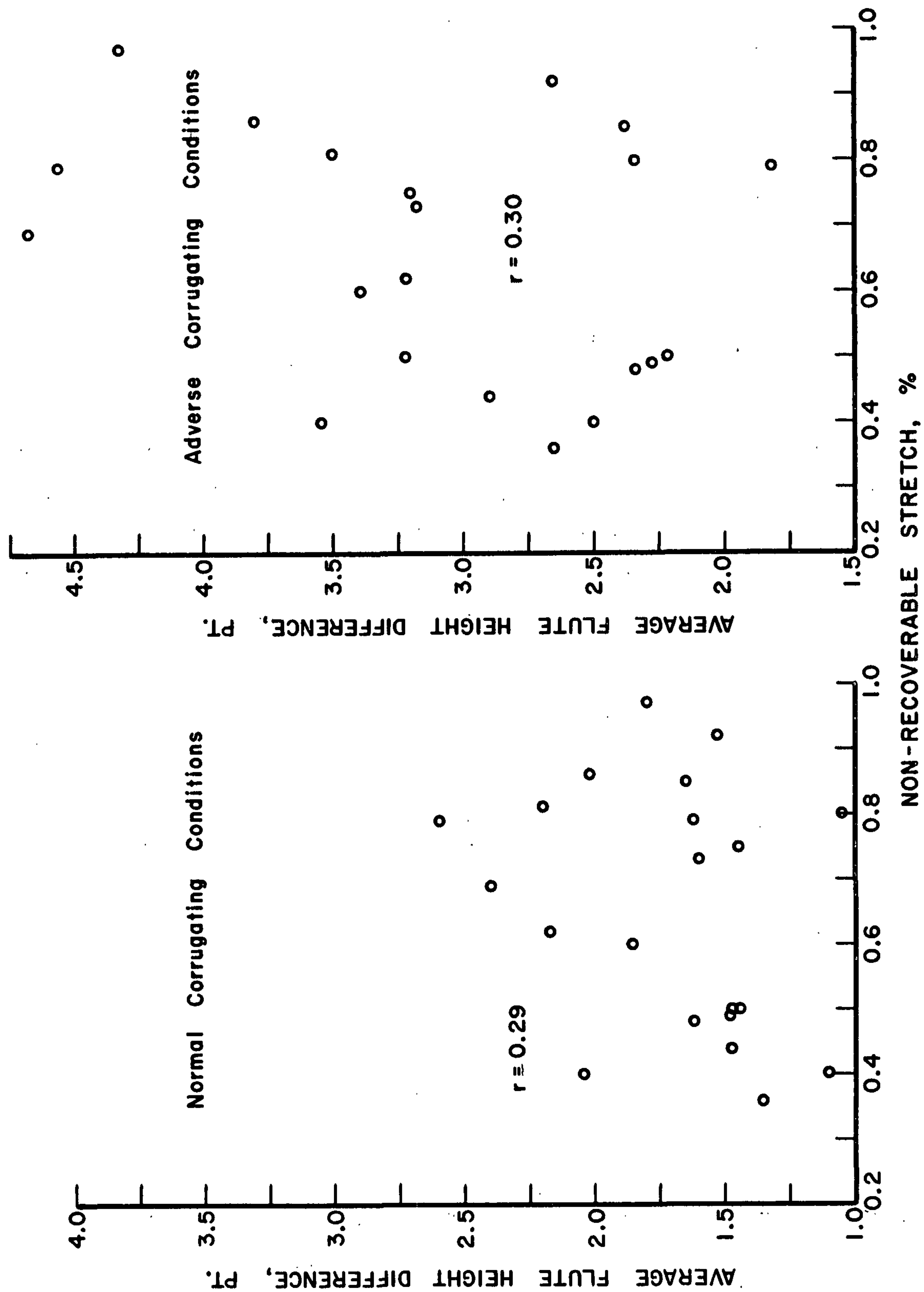

Figure 11. Relationship Between Nonrecoverable Stretch and
Average Flute Height Difference

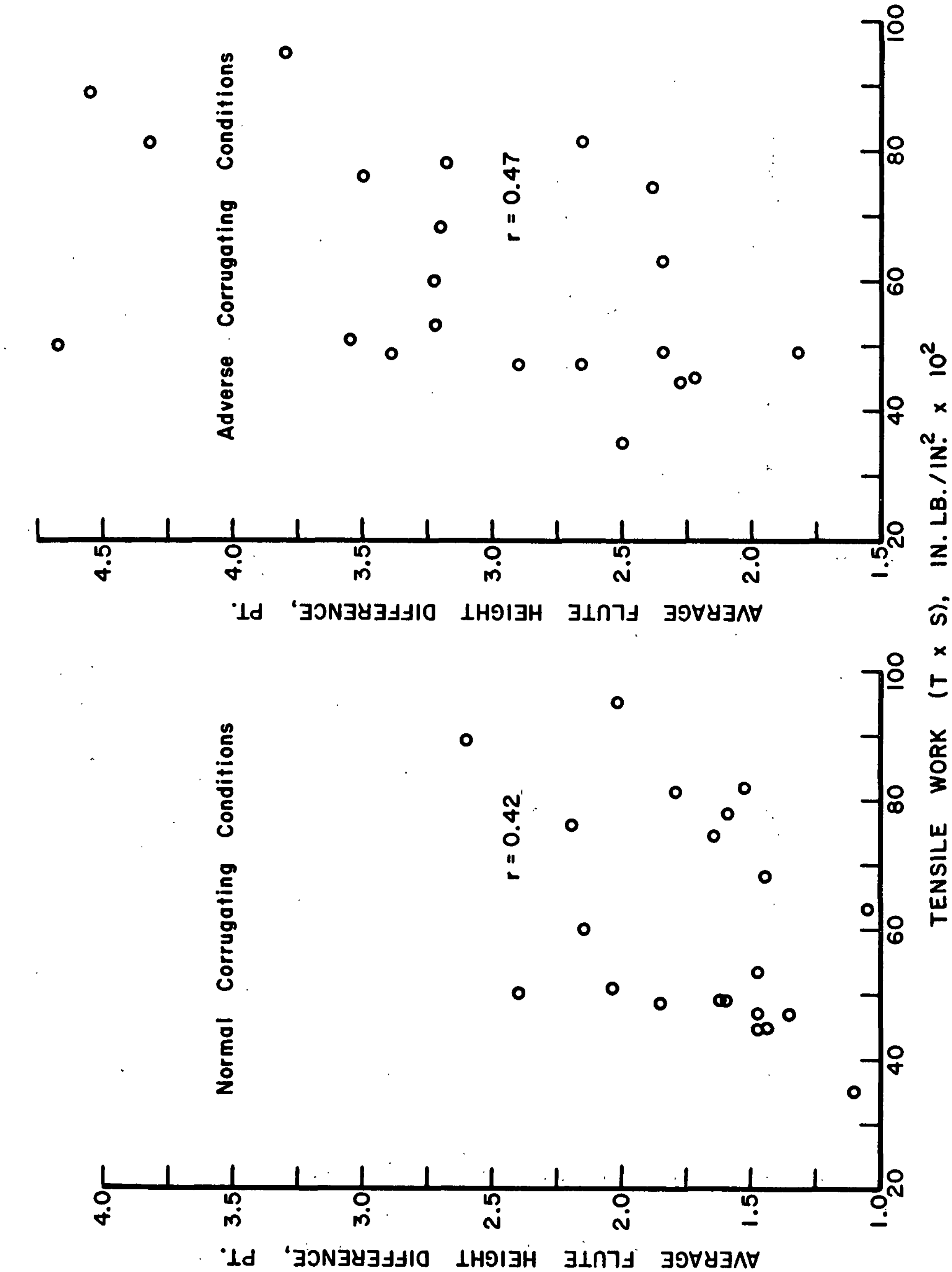

Figure 12. Relationship Between Tensile Work and Average Flute Height Difference

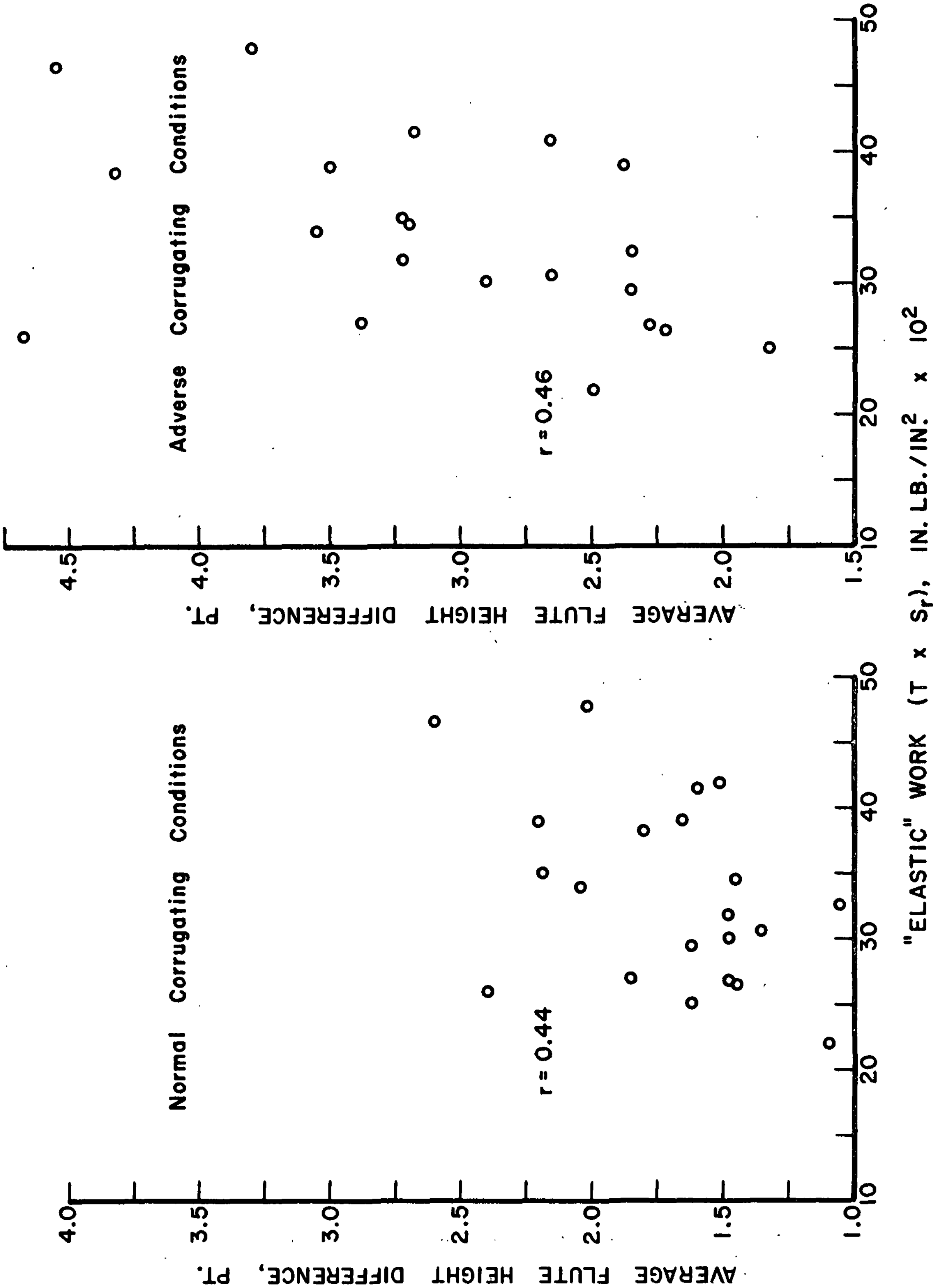

Figure 13. Relationship Between "Elastic" Work and Average Flute Height Difference

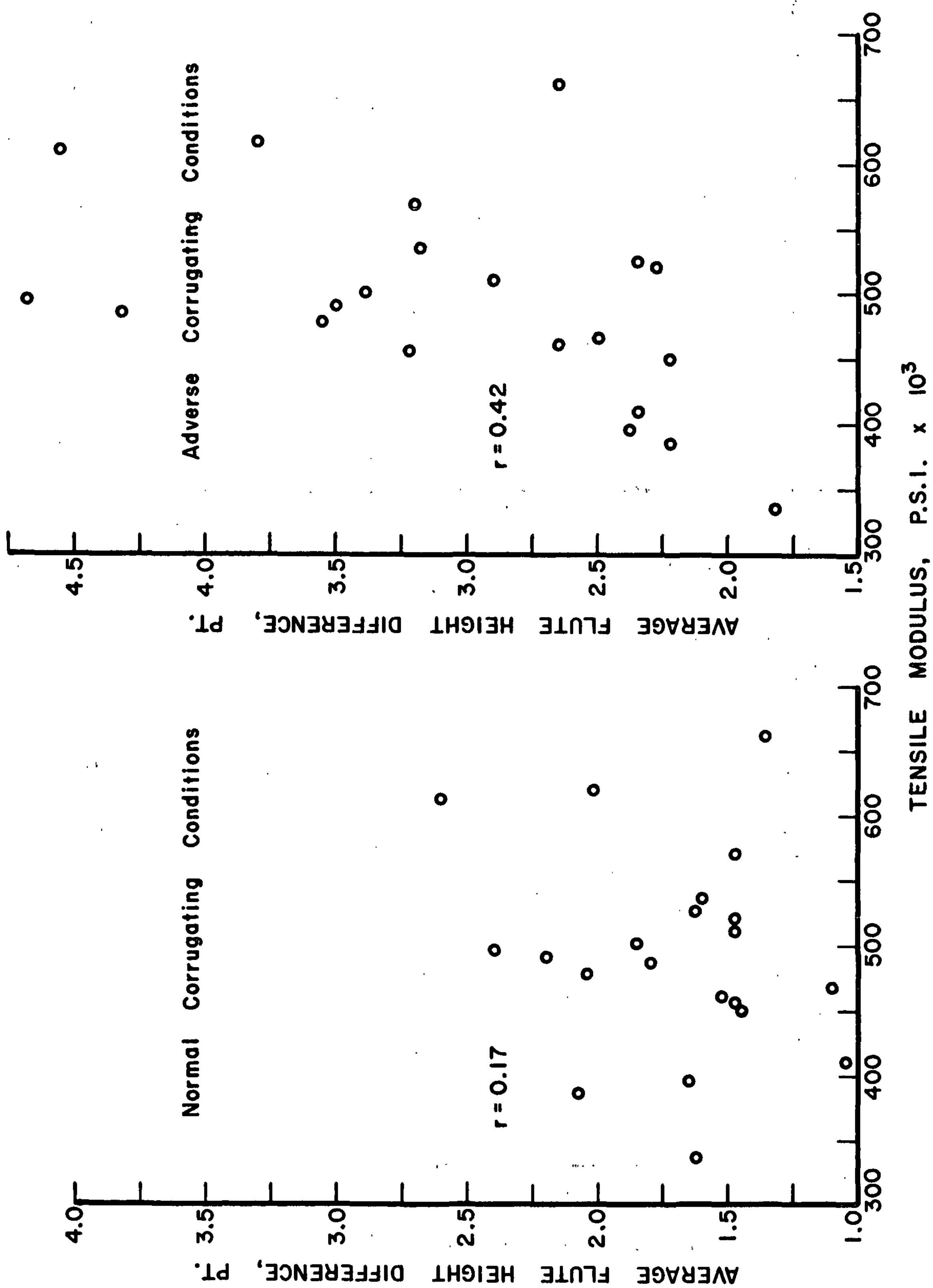

Figure 14. Relationship Between Tensile Modulus and Average Flute Height Difference

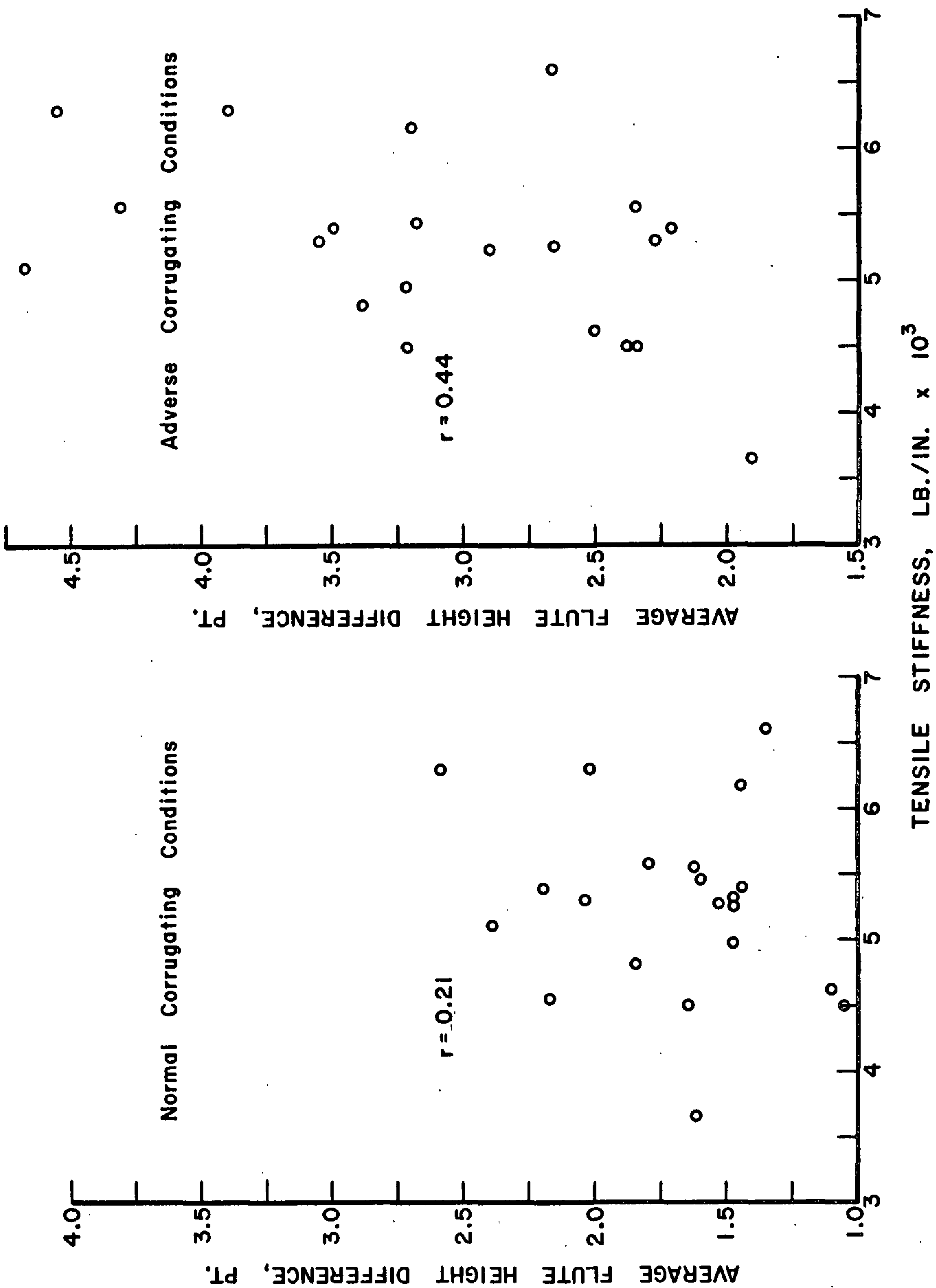

Figure 15. Relationship Between Tensile Stiffness and Average Flute Height Difference

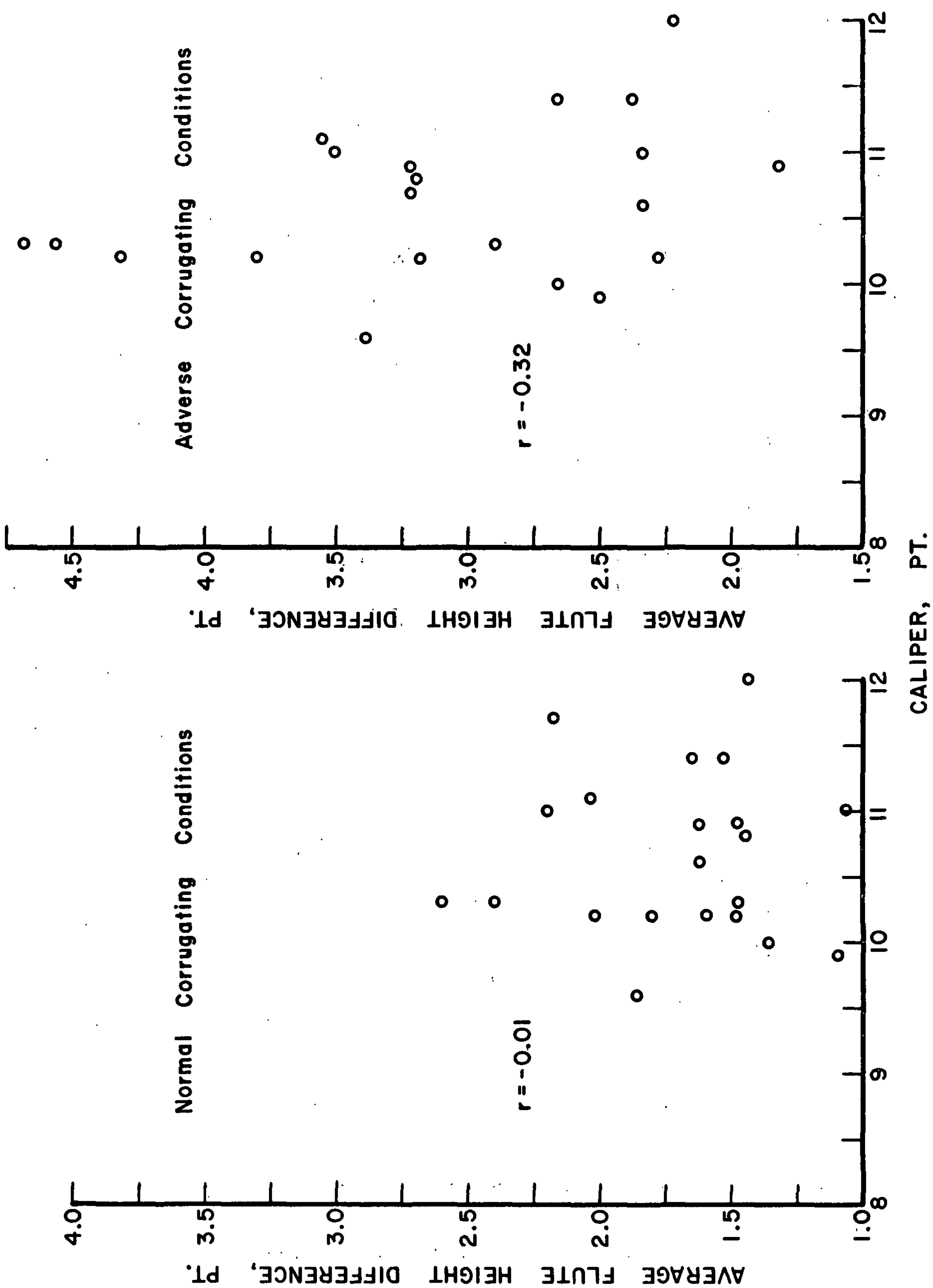

Figure 16. Relationship Between Caliper and Average Flute Height Difference

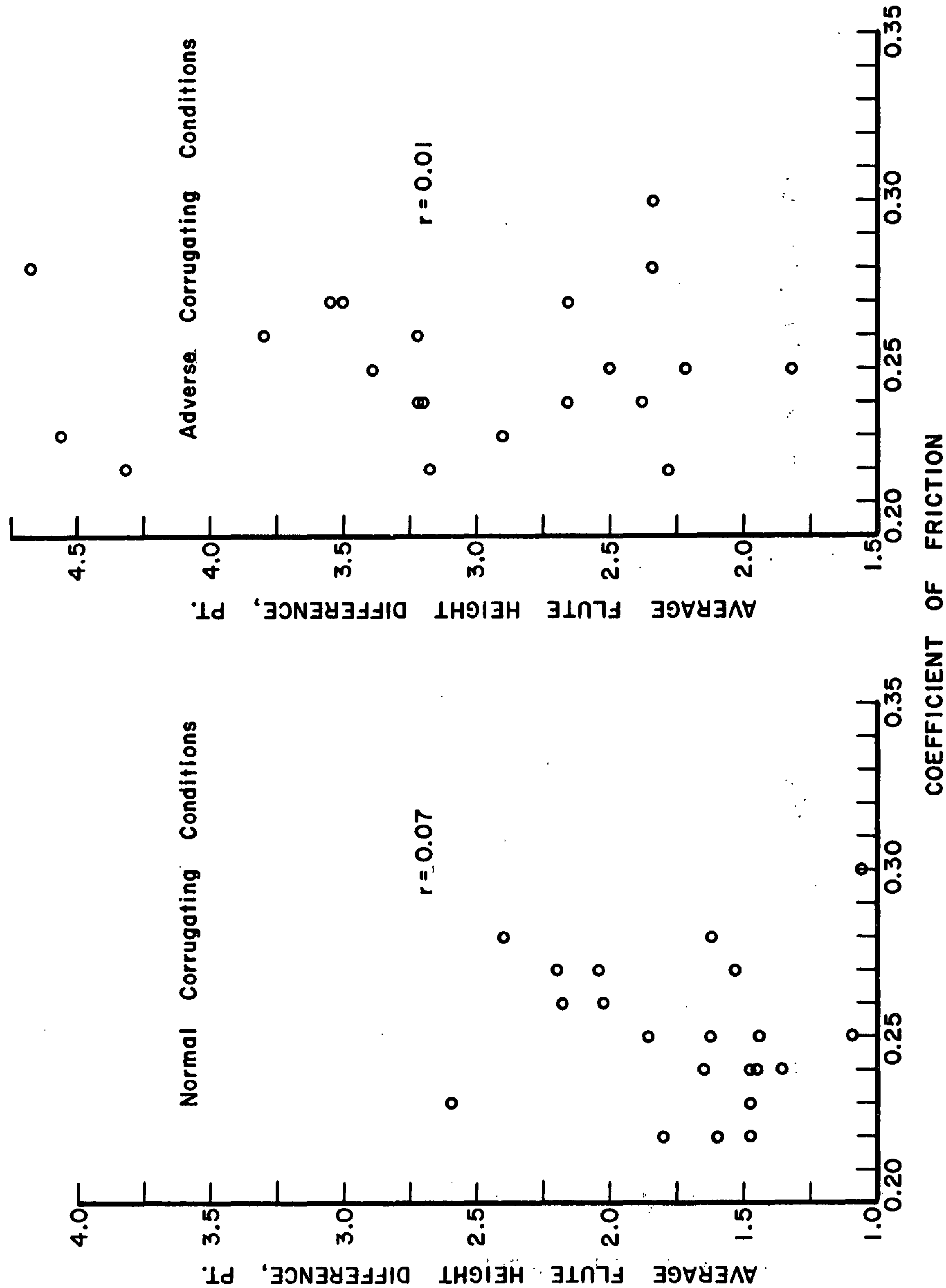

Figure 17. Relationship Between Coefficient of Friction and Average Flute Height Difference

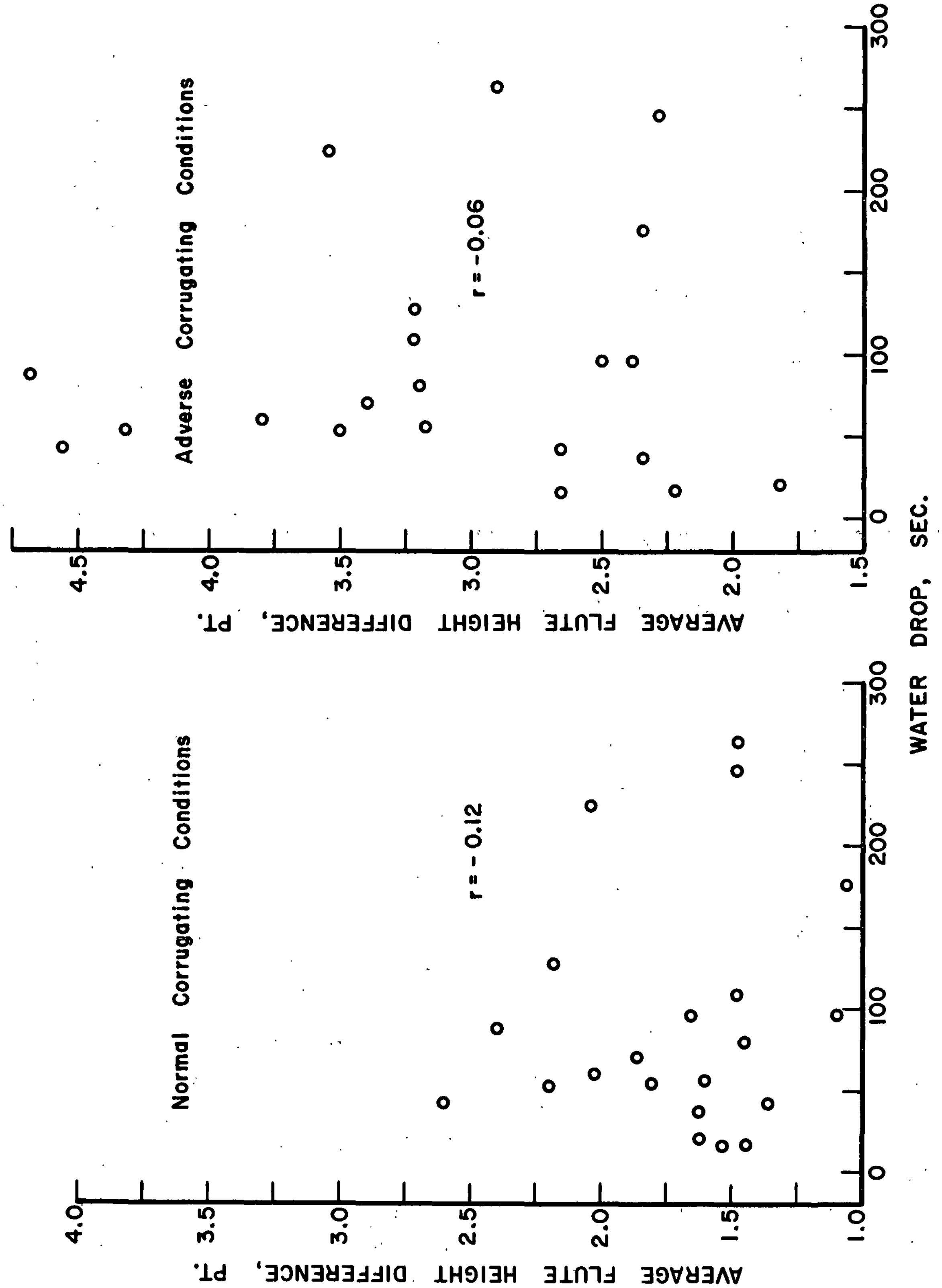

Figure 18. Relationship Between Water Drop and Average Flute Height Difference

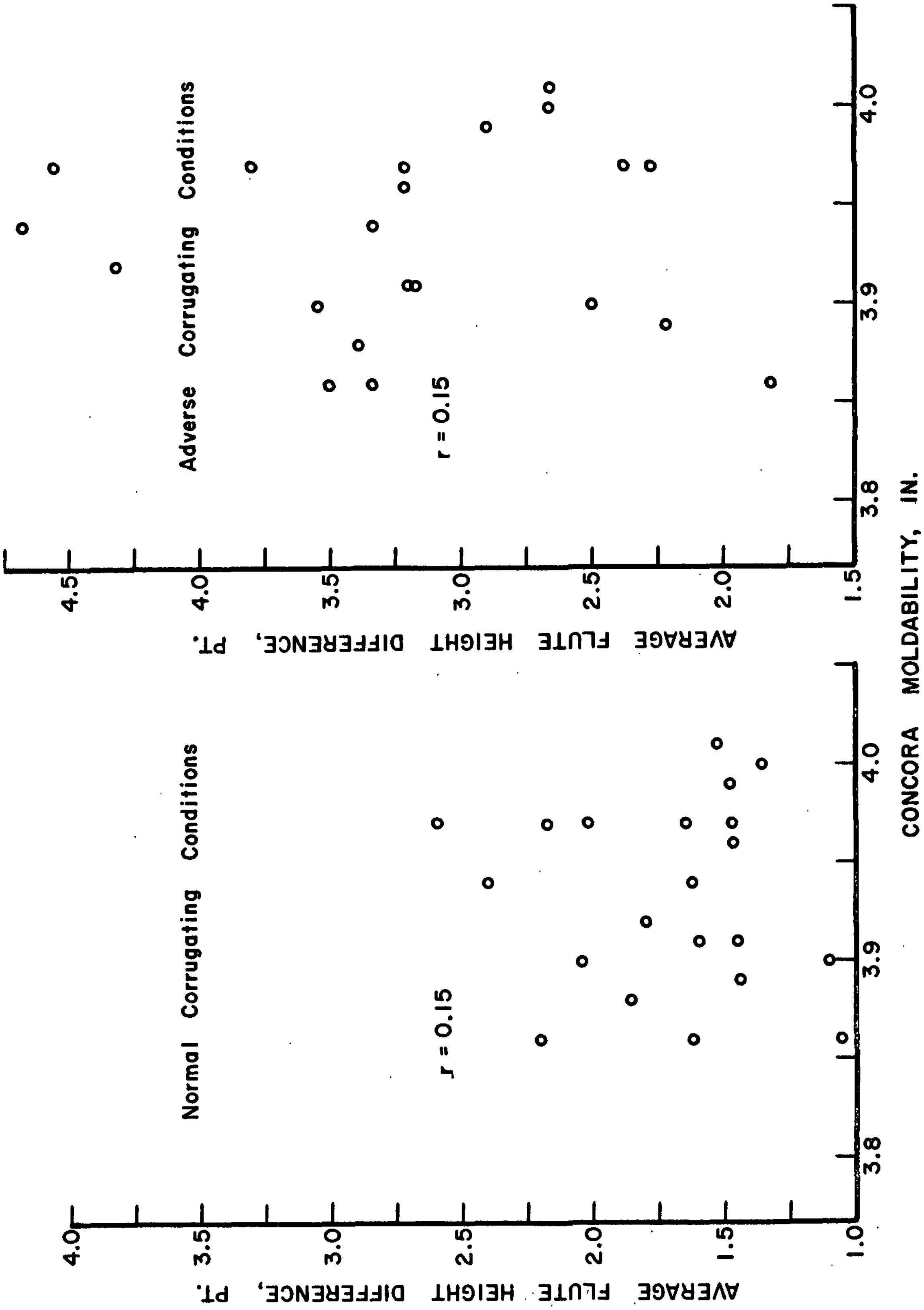

Figure 19. Relationship Between Concora Moldability and Average Flute Height Difference

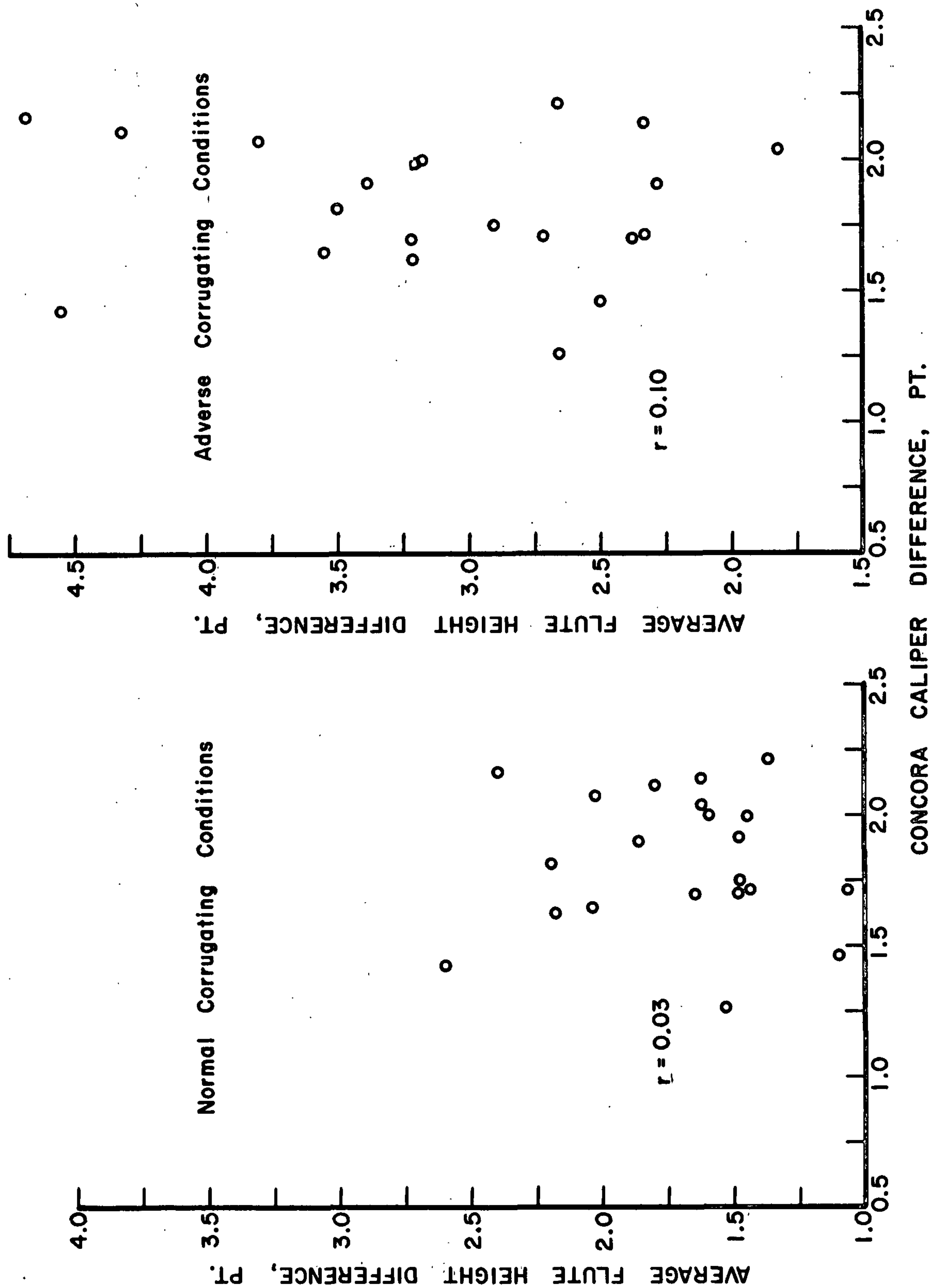

Figure 20. Relationship Between Concora Caliper Difference and Average Flute Height Difference

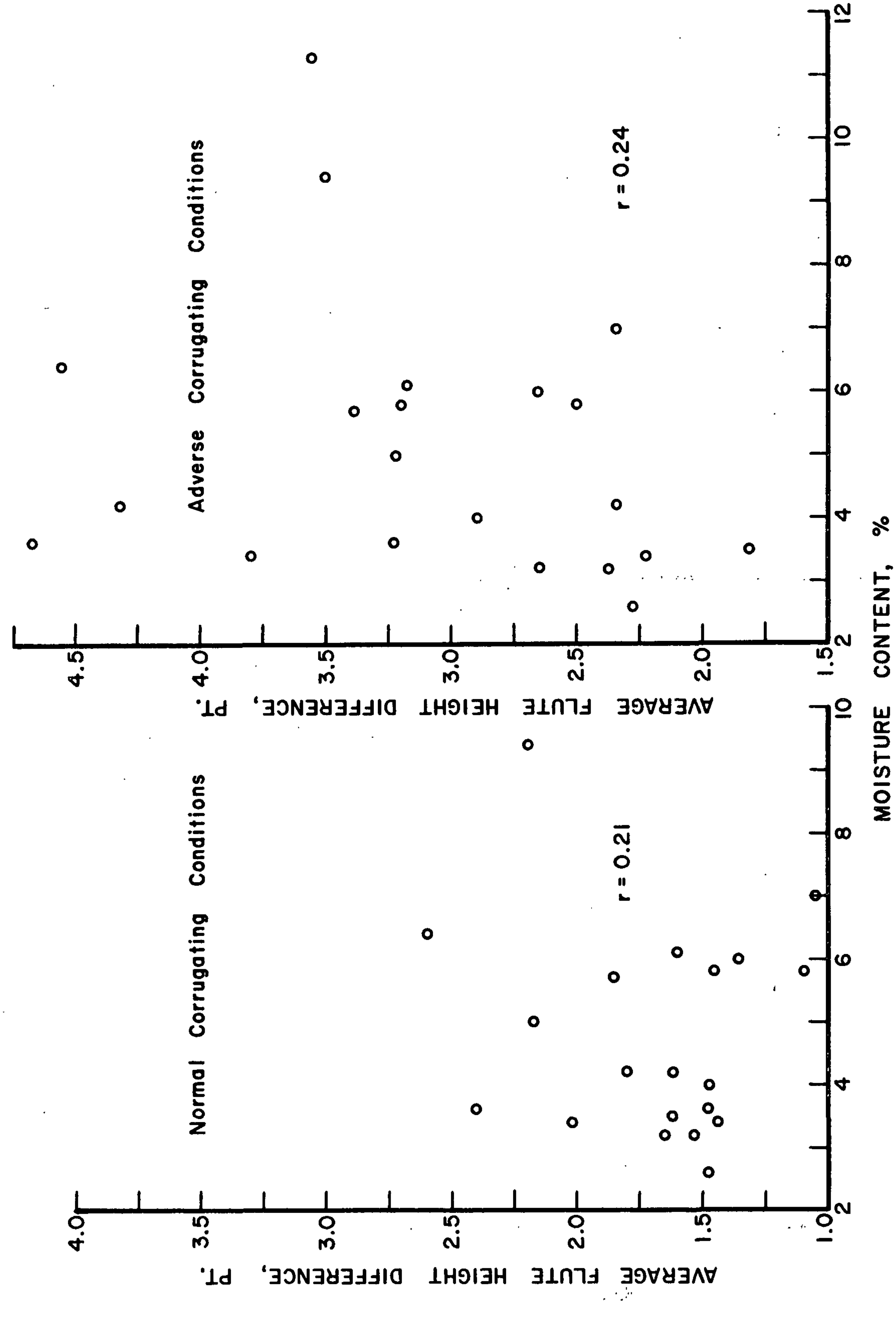

Figure 21. Relationship Between Moisture Content and Average Flute Height Difference

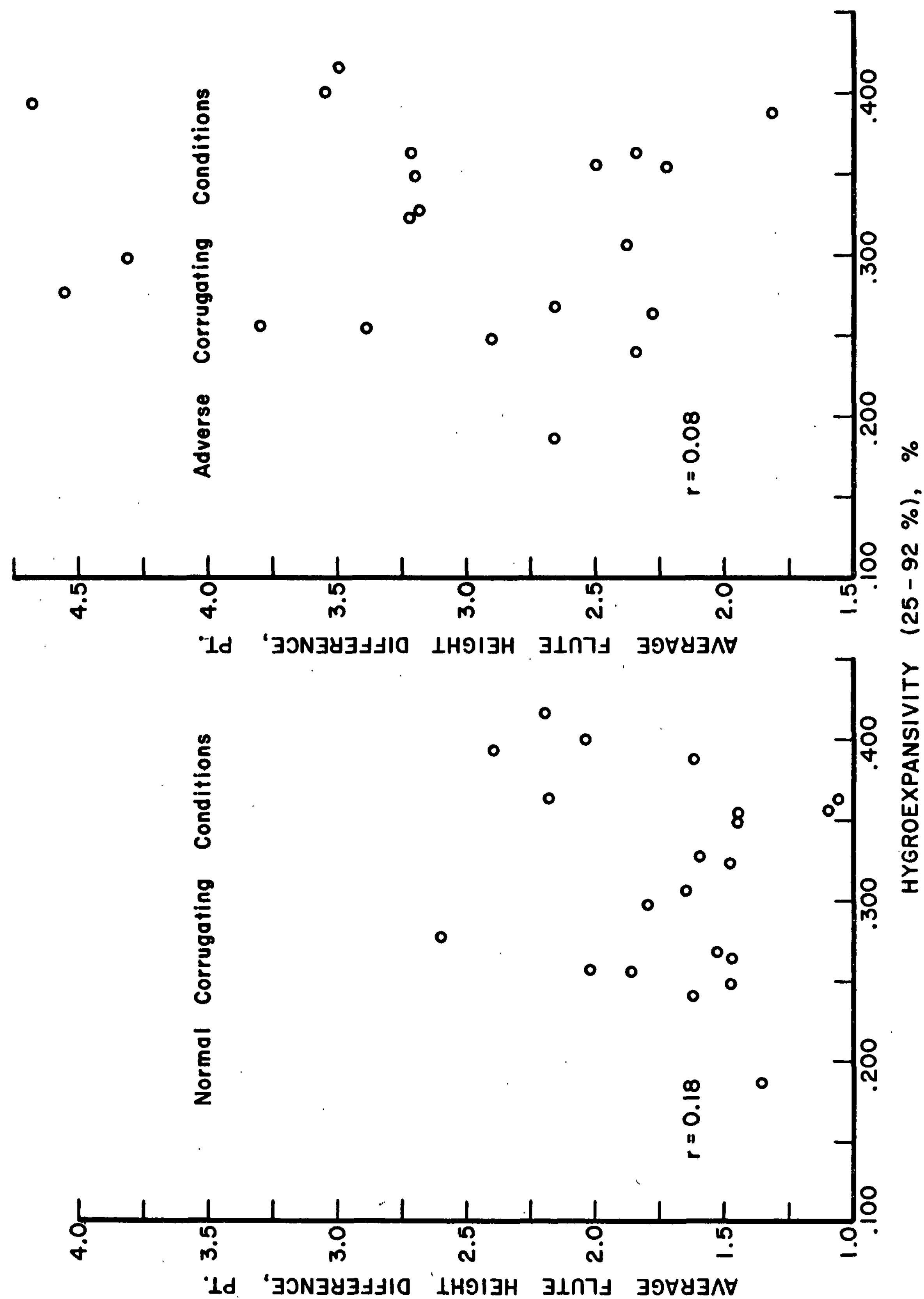

Figure 22. Relationship Between Hygroexpansivity (25-92%) and Average Flute Height Difference

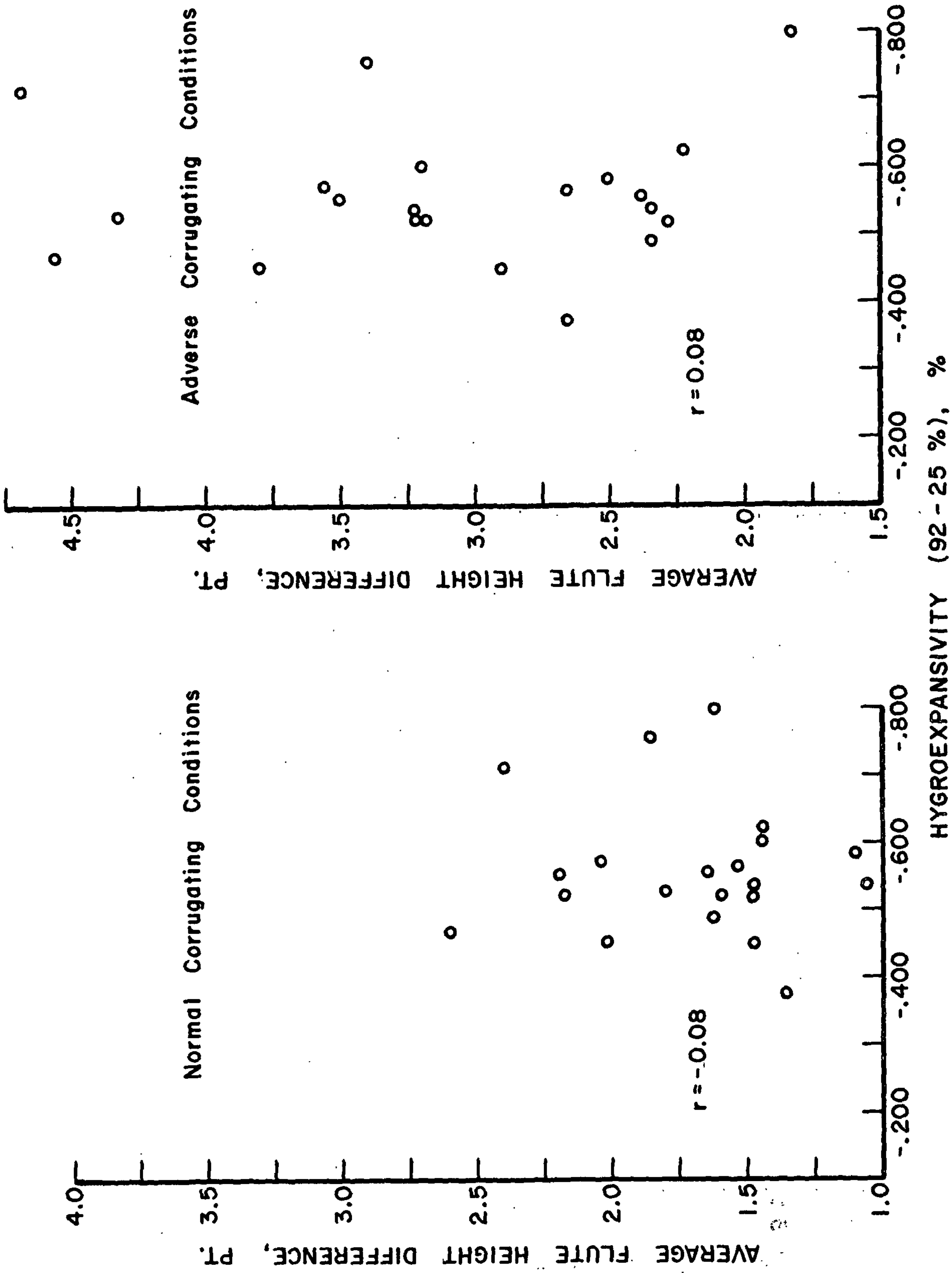

Figure 23. Relationship Between Hygroexpansivity (92-25%) and Average Flute Height Difference

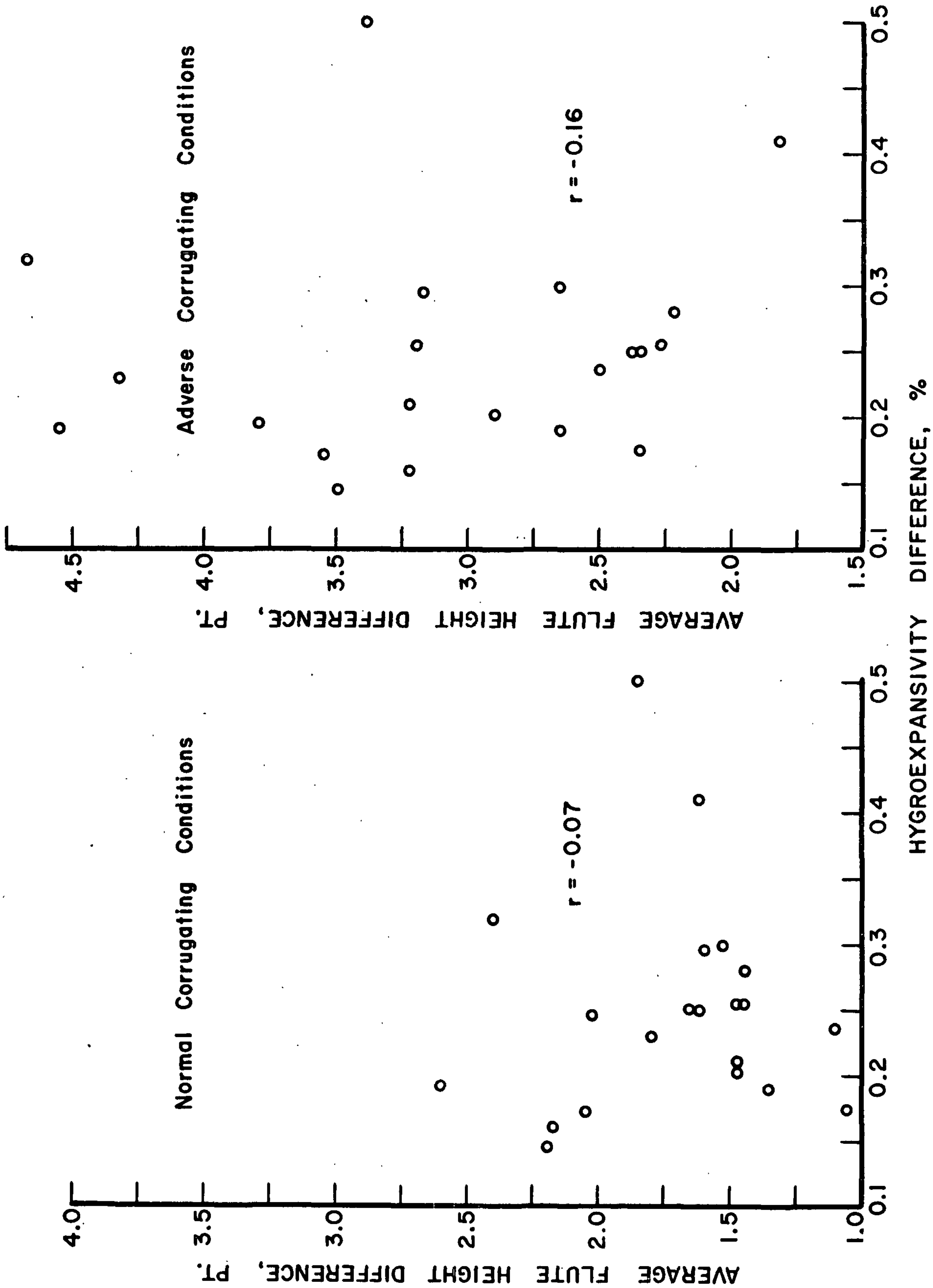

Figure 24. Relationship Between Hygroexpansivity Difference and Average Flute Height Difference

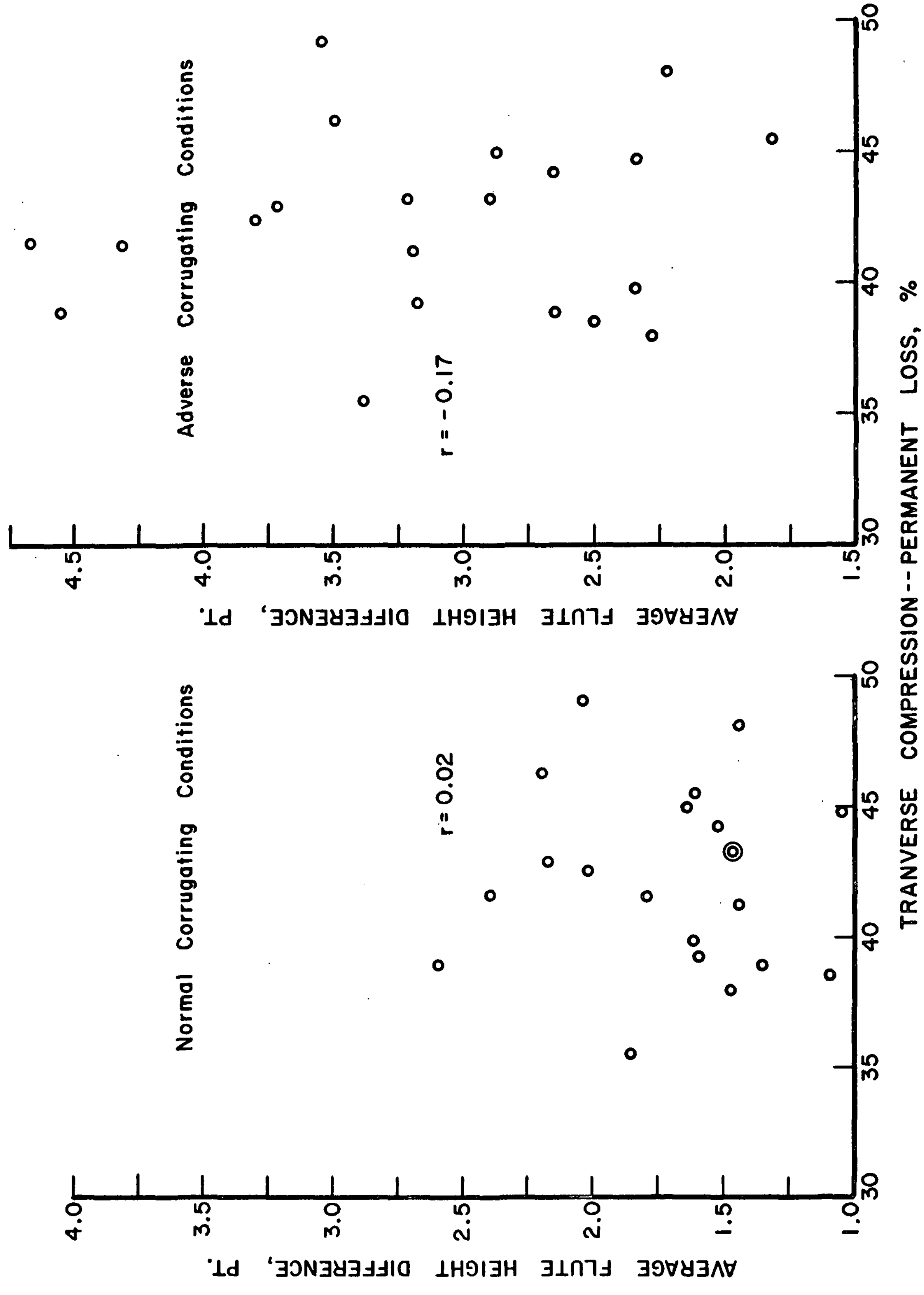

Figure 25. Relationship Between Transverse Compression and Average Flute Height Difference

The alcohol-benzene soluble material is a measure of such constituents as waxes, fats, and resins. It may possibly include portions of the so-called gums and other water-soluble components. Thus, the extractives may include a variety of substances — depending on such factors as wood species, pulping conditions, washing and possibly other factors. The extractives are present in only small amounts. In this study the percentage of extractives ranged from 0.48 to 3.34% — averaging about 1.2% for the 21 mediums in this study. It is speculated that the alcohol-benzene extractives may affect high-lows by either or both of two mechanisms as follows:

1. Certain components included in the extractives affect the frictional characteristics of the medium and, hence, influence the tensions built up in the web as it passes through the corrugating labyrinth.

2. Certain components included in the extractives become plastic at the corrugating temperature and pressure and, hence, affect the moldability of the medium and flute shape stability.

In a later section of the report it is noted that the alcohol-benzene extractives were negatively correlated at the 0.05 level with various tensile load-elongation properties — tensile, tensile stiffness, tensile work, and "elastic" work. Thus, the lower the extractives, the higher the various tensile properties and the greater the tendency toward high-low flute formation. The alcohol-benzene extractives were also negatively correlated with the Concora moldability measurement — i.e., the higher the extractives the less the Concora strip expanded in length after passing through the fluter. Friction was positively correlated with the alcohol-benzene extractives at the 0.10 level and the coefficient bordered on significance at the 0.05 level. Thus, the higher the extractives the higher the friction. From the above considerations it appears more likely that the alcohol-benzene extractives may influence high-low through the mechanisms of moldability, though the frictional mechanism cannot be entirely discounted. Perhaps it depends somewhat on exactly what components are included in the extractives.

It should also be mentioned that the correlation of alcohol-benzene extractives with the average flute height differences should be viewed with caution. Reference to Fig. 6 indicates that the correlation is probably quite dependent on the relatively high extractive values for two of the mediums, namely Rolls 688 and 708. Omission of these two values would probably lower the correlation coefficient.

With regard to the effect of formation on high-lows, it appears reasonable that the more uniform the formation the lower the high-lows. As the formation becomes more uneven, the less uniform should be the response of the web to tensions and pressures in the corrugating operation. It seems reasonable that the less uniform stress response could result in differences in flute height.

As mentioned previously, three properties of the tensile load-elongation curve exhibited significant correlations with single-face caliper differences. They were tensile strength, tensile work, and "elastic" work. It is emphasized that the tensile work value used herein represents the product of the ultimate tensile and stretch values. Therefore, it is only approximately correlated to the tensile energy absorption values which would be obtained by an integration of the area under the tensile load-deformation curve. The relationship of the two energy absorption measures depends on the curve shape. For materials where the tensile curve shapes are quite similar the measures may be quite highly correlated (7). Similar considerations apply to the "elastic" work values.

With the above in mind, it appears reasonable that high-lows may be influenced by the tension load-elongation characteristics. In general, the results indicate that the higher the tensile strength, tensile work or "elastic" work, the more likely the occurrence of high-lows. This seems to suggest that, as these parameters increase, there may be less plastic flow in the medium during the corrugating operation and, hence, the flute shape is less stable. It is rather curious that tensile strength and tensile work — failure properties — are nearly as well related to high-lows as "elastic" work, and it may be doubted whether the correlation coefficients are significantly different.

Adverse Corrugating Conditions

For the adverse corrugating conditions the following properties gave simple correlation coefficients which were statistically significant at the 0.10 or 0.05 level.

1. Tensile strength $r = 0.52$
2. Tensile work $r = 0.47$
3. "Elastic" work $r = 0.46$
4. Tensile stiffness $r = 0.44$
5. Tensile modulus $r = 0.42$

As mentioned previously, the adverse corrugating conditions were included in the study because they may be indicative of medium performance under less than "ideal" operating conditions. Under adverse conditions the above indicates that only the tension load-elongation characteristics gave statistically significant correlations with average flute height differences. The direction of the effect was the same for all properties — i.e., an increase in tensile strength, work, modulus, or stiffness was associated with a trend to greater average flute height differences.

The above results differ from the results obtained under normal operating conditions in that the coefficients for alcohol-benzene extractives and formation did not reach significance at even the 0.10 level. Perhaps the higher tensions employed in the adverse condition resulted in greater emphasis on tension properties.

Composite of Normal and Adverse Operating Conditions

When the normal and adverse conditions were composited to provide an overall measure of medium high-low performance, the following properties exhibited significant correlation coefficients at the 0.10 level or better:

1. Tensile strength $r = 0.51$
2. Tensile work $r = 0.48$
3. "Elastic" work $r = 0.48$
4. Tensile stiffness $r = 0.38$
5. Alcohol-benzene extractives $r = -0.38$

Thus, the highest coefficients were obtained with tensile strength, tensile work, and "elastic" work. All coefficients were positive indicating that the higher the property the greater the average flute height differences. As may be noted, the alcohol-benzene extractives exhibited statistical significance at the 0.10 level. Its coefficient of -0.38 was intermediate between its coefficients for the normal and adverse conditions (-0.53 and -0.28, respectively).

As may be noted in Table V, three properties gave correlation coefficients which were statistically significant at the 0.10 level or better in all three analyses. They were (1) tensile strength, (2) tensile work, and (3) "elastic" work. The coefficients for the three properties were roughly of the same order of magnitude within a given analysis. It is doubtful whether the small differences in correlation coefficient between these three properties are of practical or statistical significance.

Correlation Between Medium Properties

The intercorrelation coefficients between the various medium properties are shown in Table VI. In the preceding discussion it was noted that only a few of the properties studied were significantly correlated with average flute height differences at the 0.10 level or better. The properties were as follows:

1. Alcohol-benzene extractives
2. Formation
3. Tensile strength
4. Tensile work
5. "Elastic" work
6. Tensile stiffness
7. Tensile modulus

Centering attention on the above properties it may be noted that alcohol-benzene extractives exhibited significant correlations at the 0.05 level with Concora moldability, tensile strength, tensile stiffness, tensile work, and "elastic" work. In these cases, negative coefficients were obtained indicating that the higher the amount of extractives, the lower the test property. These sign differences are consistent with the way the properties were related to flute height differences in the previous section — i.e., high alcohol-benzene extractives and low tensile or tensile work values were associated with lower caliper differences. It is not known whether there is any real relationship between amount of extractives and the other properties mentioned above. However, it appears possible that both the extractives and tensile load-elongation properties are affected by other variables in the pulping and papermaking operations in such a way as to lead to the relatively weak intercorrelations.

For the data in Table VI, formation was not significantly related to any of the other properties where coefficients were obtained.

TABLE VI

CORRELATION BETWEEN MEDIUM PROPERTIES

	Moisture	Caliper	Concora Caliper Diff.	Concora Moldability	Trans. Comp.	Friction	Water Drop	Tensile	Stretch	Recov. Stretch	Non-Recov. Stretch	Tensile Modulus	Tensile Stiffness	Secant Modulus	Tensile Work	Elastic Work	Formation	Alcohol-Benzene Ext.	Hygroexpansivity 25-92%	Hygroexpansivity 92-25%
Moisture	1.00	-0.01	-0.15	-0.44	0.23	0.33	0.17	0.16	-0.08	0.08	-0.15	0.13	0.14	0.19	0.03	0.14	-0.04	0.02	0.40	0.08
Caliper		1.00	-0.41	-0.03	0.80	0.13	-0.04	-0.07	0.23	0.37	0.16	-0.58	-0.30[a]	-0.53	0.08[a]	0.09[a]	0.21	-0.23	0.45	-0.09
Concora caliper diff.			1.00	-0.12	-0.26	-0.36	-0.11	0.00	-0.12	-0.32	-0.02	0.31	--	0.26	--	--	-0.04	-0.14	-0.18	-0.04
Concora moldability				1.00	-0.20	-0.29	0.13	0.44	-0.03	0.09	-0.06	0.40	0.43	0.41	0.23	0.36	0.11	-0.47	-0.66	0.60
Transverse compression					1.00	0.16	0.12	-0.05	0.20	0.33	0.13	-0.50	-0.27	-0.43	0.07	0.09	0.26	-0.21	0.57	-0.11
Friction						1.00	-0.14	-0.18	-0.04	-0.03	-0.03	-0.16	0.20[a]	-0.17	-0.11[a]	-0.13[a]	0.02	0.43	0.34	-0.14
Water drop							1.00	-0.19	-0.32	-0.08	-0.38	-0.10	--	0.14	--	--	-0.19	0.03	0.03	0.21
Tensile								1.00	0.46	0.45	0.43	0.66	0.78	0.34	0.84	0.92	0.05	-0.58	-0.34	0.62
Stretch									1.00	0.88	0.96	-0.22	-0.11	-0.63	0.86	0.72	-0.24	-0.28	0.19	-0.09
Recoverable stretch										1.00	0.73	-0.31	-0.20	-0.56	0.77	0.76	-0.24	-0.29	0.17	0.09
Nonrecoverable stretch											1.00	-0.16	--[a]	-0.60	--[a]	--[a]	-0.20	-0.28	0.16	-0.17
Tensile modulus												1.00	0.94	0.85[a]	0.25	0.35	0.14	-0.30	-0.59[a]	0.56[a]
Tensile stiffness													1.00	--	0.38[a]	0.47[a]	0.25	-0.47	--	--
Secant modulus														1.00	--	--	0.27	-0.15	-0.61[a]	0.62[a]
Tensile work															1.00	0.95	-0.12	-0.47	--	--
Elastic work																1.00	-0.08	-0.53	--[a]	--[a]
Formation																	1.00	0.02	-0.16	0.19
Alcohol-benzene extracts																		1.00	0.23	-0.21
Hygroexpansivity (25-92%)																			1.00	-0.54
Hygroexpansivity (92-25%)																				1.00

[a]Coefficient not determined.

Note: 0.01, 0.05 and 0.10 levels of significance are 0.549, 0.433 and 0.369, respectively; underlined values are significant at the 0.05 level.

With regard to the tensile load-elongation properties, it may be noted that in frequent instances the properties are highly intercorrelated among themselves as would be expected. For example, tensile strength is highly correlated (beyond the 0.01 level) with tensile modulus, stiffness, work, and "elastic" work. Because tensile strength was one of the factors entering into both work values, the high correlation is not surprising. Tensile work was very highly correlated with "elastic" work—reflecting the fact that (a) stretch and recoverable stretch were highly intercorrelated, and (b) tensile strength was used in calculating both work values. For the data of this study, therefore, it appears that tensile strength, tensile and "elastic" work are so highly intercorrelated that they may be considered as practically equivalent properties from a correlation standpoint. The same statement could be made for a number of other pairs of tensile load-elongation properties — for example, tensile modulus and stiffness, or stretch, recoverable stretch, and nonrecoverable stretch.

MULTIPLE CORRELATIONS

Normal Corrugating Conditions

Stepwise linear multiple regression techniques were employed to study the relationship between average flute height differences and combinations of medium properties. Essentially, the program used directs the computer to search through the set of independent variables to select the variable best related to the dependent variable; the remaining variables are then examined to select the next best independent variable. This process is repeated until all the variables are included or until the multiple correlation coefficient or F test attain some specified value. At each step, statistics are provided to test the significance of each variable in the regression as well as the overall significance of the regression. Except in a few instances, the regression equations discussed in the following pages were those in which all variables were statistically significant at the 0.10 level or better.

For normal corrugating conditions, the regression equations shown in Table VII met the above criterion. For each equation the regression coefficients are shown together with the $\underline{t}$ value for each coefficient, the multiple $\underline{F}$ and multiple correlation coefficient $\underline{R}$. A value of $\underline{R}$ which has been adjusted for degrees of freedom is also shown. Average prediction errors in percent are shown for a number of the equations.

Equation (1) is a single-factor relationship based on the alcohol-benzene extractives and exhibits a correlation coefficient of 0.53. Equation (2) incorporates formation, and Equation (3) incorporates formation and friction with the alcohol-benzene extractives. All factors were significant at the 0.05 level or better. The two-factor relationship [Equation (2)] had a multiple $\underline{R}$ of 0.68 and the three-factor relationship had a multiple $\underline{R}$ of 0.73. Thus, the addition of the extra factors produced modest improvements in the multiple correlation coefficient. The average prediction error was 13.2% using the three-factor relationship.

Equation (4) incorporated two additional variables — namely, hygroexpansivity (25-92% R.H.) and caliper. While a further modest improvement in the multiple $\underline{R}$ occurred, the individual properties were only significant at the 0.10 level with the exception of the alcohol-benzene extractives (significant at the 0.01 level). It may also be noted that the improvement in average prediction accuracy was fairly small — from 13.2 to 12.0%.

Due to the moisture changes taking place in the medium in the single-facing operation, it appears reasonable that hygroexpansivity could be one of the properties affecting high-lows. Thus, greater dimensional instability under changing moisture and R.H. conditions might be expected to result in a greater tendency toward high-lows. There is also reason to believe that within limits, the caliper of the medium may

TABLE VII

REGRESSION EQUATIONS WITH ALL FACTORS SIGNIFICANT AT THE 0.10 LEVEL OR GREATER
(Normal corrugating conditions)

No.	Regression Coefficients Var. 1	Var. 2	Var. 3	Var. 4	Var. 5	Constant	"t" Value Var. 1	Var. 2	Var. 3	Var. 4	Var. 5	F Ratio	Mult. Corr. Coefficient R	R_{adj}	Av. Prediction Error, %
1	-0.29AB	--	--	--	--	2.05	2.70[b]	--	--	--	--	7.31[b]	0.53	0.53	15.2
2	-0.29AB	-0.083FO	--	--	--	2.88	3.00[a]	2.51[b]	--	--	--	7.83[a]	0.68	0.66	14.2
3	-0.38AB	-0.083FO	6.25FR	--	--	1.39	3.88[a]	2.76[b]	2.13[b]	--	--	7.77[a]	0.76	0.73	13.2
4	-0.46AB	-0.058FO	6.01FR	2.32H2	-0.22CA	2.93	4.56[a]	1.85[c]	2.08[c]	1.85[c]	1.77[c]	6.10[a]	0.82	0.77	12.0
5	0.026TE	--	--	--	--	0.63	1.92[c]	--	--	--	--	3.70[c]	0.40	0.40	17.9
6	0.027TE	-0.089FO	--	--	--	1.46	2.30[b]	2.50[b]	--	--	--	5.50[b]	0.62	0.59	15.4
7	0.0098TS	--	--	--	--	1.11	2.00[c]	--	--	--	--	4.02[c]	0.42	0.42	17.1
8	0.0087TS	-0.077FO	--	--	--	1.95	1.91[c]	2.07[c]	--	--	--	4.49[b]	0.58	0.55	16.2
9	0.025TR	--	--	--	--	0.88	2.12[b]	--	--	--	--	4.49[b]	0.44	0.44	17.0
10	0.023TR	-0.079FO	--	--	--	1.73	2.14[b]	2.18[b]	--	--	--	5.07[b]	0.60	0.57	15.9

[a]Significant at the 0.01 level.

[b]Significant at the 0.05 level.

[c]Significant at the 0.10 level.

Note: Equation form: $\underline{Y} = \underline{a} + \underline{bx_1} + \underline{rx_2}$ ... when $\underline{Y}$ = average flute height difference and $\underline{x_1}$, $\underline{x_2}$ ... are medium properties
Symbols are defined below:

AB = alcohol-benzene ext.
FO = formation
FR = friction
H2 = hygroexpansivity, 25-92%

CA = caliper
TE = tensile
TS = tensile work
TR = elastic work

influence high-low formation inasmuch as the degree of molding in the labyrinth may be affected by changes in caliper. However, the results in Table VII suggest that hygroexpansivity and caliper are of secondary importance — relative to the alcohol-benzene extractives, formation and friction. On this basis it may be more useful from a practical standpoint to prefer Equation (2) and/or Equation (3) which involve a lesser number of properties.

As mentioned previously, the correlation of average flute height differences with alcohol-benzene extractives may be influenced to a considerable extent by two of the samples which exhibited considerably higher extractives content than the other mediums. There is some risk, therefore, that the apparent importance of alcohol-benzene extractives may be overemphasized in this set of data. Additional data on other mediums would be needed to clarify this point.

However, with this in mind, additional multiple regressions were investigated using various tension load-elongation properties. In general, it was found that two-factor regressions with both factors significant at the 0.10 level or better could be formed using

1. Tensile strength and formation [see Equation (6)];
2. Tensile work and formation [see Equation (8)];
3. "Elastic" work and formation [see Equation (10)].

In the stepwise regressions, it was found that other properties added to the above regressions, were not statistically significant at even the 0.10 level. When Equations (6), (8), and (10) are compared, it may be noted that Equation (6) involving tensile strength and formation exhibited a slightly higher $\underline{F}$ value and multiple $\underline{R}$ and a slightly lower average prediction error than the other two equations.

On the basis of these results for normal corrugating conditions, it appears that the following conclusions may be drawn:

1. The best predictions of average flute height differences with all properties significant at the 0.05 level or better were obtained with the following combination of properties: (a) alcohol-benzene extractives, (b) formation, and (c) friction. The average prediction error was 13.2%.

2. In (1) the single-face caliper differences increased as:

   a. alcohol-benzene extractives decreased;

   b. formation became less uniform;

   c. friction increased.

3. Slight improvements in the predictive accuracy of (1) above could be achieved by also considering hygroexpansivity and caliper.

4. As an alternative to regression equations based on alcohol-benzene extractives as one of the properties, it appeared that the combination of tensile strength and formation gave the next best predictions of average flute height differences. The average predictive difference was 15.4%.

5. In (4) the average flute height differences increased as

   a. tensile strength increased;

   b. formation became less uniform.

6. Tensile work or "elastic" tensile work in combination with formation gave regression equations which exhibited only slightly greater prediction errors on the average than the equation based on tensile strength and formation.

<u>Adverse Corrugating Conditions</u>

The better regression equations obtained in the stepwise analysis of the data obtained under adverse operating conditions are summarized in Table VIII. It may be recalled that, under adverse operating conditions, tensile strength gave the

TABLE VIII

MULTIPLE REGRESSION EQUATIONS FOR ADVERSE CORRUGATING CONDITIONS

	Regression Coefficients				t Value			F	Mult. Corr. Coefficient		Av.
No.	Var. 1	Var. 2	Var. 3	Constant	Var. 1	Var. 2	Var. 3	Ratio	R	R_{adj}	Prediction Error, %
11	0.066TE	--	--	0.30	2.68[b]	--	--	7.17[a]	0.52	0.52	17.1
12	0.097TE	-3.12H9	--	-2.73	3.23[a]	1.66[d]	--	5.30[a]	0.61	0.58	17.3
13	0.096TE	-3.31H9	-0.38CA	1.28	3.36[a]	1.85[c]	1.69[d]	4.85[a]	0.68	0.63	15.8
14	0.0216TS	--	--	1.76	2.29[b]	--	--	5.26[b]	0.47	0.47	17.9
15	0.0230TS	-0.452CA	--	6.50	2.58[b]	1.87[c]	--	4.72[b]	0.59	0.56	17.3
16	0.0249TS	-0.666CA	+4.64H2	7.20	2.94[a]	2.58[b]	1.79[c]	4.60[b]	0.67	0.62	16.5

[a]Significant at the 0.01 level.

[b]Significant at the 0.05 level.

[c]Significant at the 0.10 level.

[d]Significant at the 0.20 level.

Note: Regression equation form $Y = a + bx_1 + rx_2$ ... where Y = average flute height difference and x_1, x_2, etc. are medium properties.

Symbols are defined below:

TE = tensile strength
H9 = hygroexpansivity, (92-25%)
H2 = hygroexpansivity, (25-92%)
CA = caliper
TS = tensile work

highest simple correlation with the average flute height differences. Therefore, Equation (11) shows the single-factor relationship based on tensile strength alone. In Equation (12) the second property entered in the stepwise regression was hygroexpansivity (92-25%) — i.e., the percentage change in length associated with a decrease in R.H. from 92 to 25%. It may be noted, however, in Equation (12) that hygroexpansivity exhibited a low level of significance (0.20 level). Also, there was no improvement in the average prediction error — from 17.1% for tensile strength alone to 17.3% for tensile strength plus hygroexpansivity (92-25%) — even though there was an increase in the multiple correlation coefficient.

In Equation (13) three properties were incorporated in the stepwise regression, namely, tensile strength, hygroexpansivity (92-25%), and caliper. In this case only tensile strength exhibited a high level of significance (0.01 level); the levels of significance were only 0.10 and 0.20 for hygroexpansivity (92-25% R.H.) and caliper, respectively. The average prediction error was 15.8% for the three-factor relationship.

In Equations (11)-(13) it may be noted that average flute height differences increase as tensile strength increases and as the hygroexpansivity contraction from 92 to 25% R.H. increases. [Note: The hygroexpansivity 92-25% R.H. values were given a negative sign to denote contraction, therefore, the negative sign on the coefficient and test value result in positive increase in flute height difference when the contraction increases.] The negative sign on medium caliper indicates that the flute height differences increase as caliper decreases.

It may be recalled that tensile work (and elastic work) also exhibited significant simple correlations with the caliper differences obtained under adverse conditions. With this in mind a series of stepwise regressions were also obtained using tensile work as a starting point. The resulting regression equations are identified as Equations (14), (15), and (16) in Table VIII. Equation (14) is a single-factor relationship based on tensile work and exhibits a correlation coefficient of 0.47. Equation (15) incorporated caliper, and Equation (16) incorporated caliper and hygroexpansivity (25-92% R.H.) with tensile work. In both Equations (15) and (16), the last property entered in the regression was only significant at the 0.10 level. The two-factor relationship had a multiple $\underline{R}$ of 0.59 and the three-factor relationship had a multiple $\underline{R}$ of 0.67. Thus, the additional factors produced modest improvements in the multiple correlation coefficient and average prediction accuracy.

As may be noted, Equations (13) and (16) are not consistent with regard to hygroexpansivity. In one instance the dimensional stability under decreasing moisture conditions is involved and in the other the dimensional stability under increasing conditions is involved. Apparently, this may result from differences in the way the various properties involved are intercorrelated. While it seems reasonable that hygroexpansivity may be a factor in high-lows, it appears that they exert a rather minor influence based on their relatively low significance levels. A somewhat similar conclusion was reached when the data for the normal corrugating conditions were analyzed.

Therefore, on the basis of these results for adverse operating conditions, it appears that the following conclusions may be drawn:

1. Stepwise multiple regression analysis indicated that some improvement in predictive accuracy (relative to tensile strength or work alone) could be achieved with either of the following sets of properties:

   a. tensile strength, hygroexpansivity (25-92%) and caliper;

   b. tensile work, hygroexpansivity (25-92%) and caliper.

However, in these three-factor regressions only tensile strength and tensile work were highly significant (0.01 level).

2. The average prediction error of the three-factor equation involving tensile strength, hygroexpansivity (92-25%) and caliper was 15.8. Using tensile strength alone, the average prediction error was 17.1%.

3. The average prediction error of the three-factor equation involving tensile work, hygroexpansivity (25-92%) and caliper was 16.5%. Using tensile work alone, the average prediction error was 17.9%.

4. Based on these results, it appears that the additional properties, namely, the two hygroexpansivites and caliper, effected rather modest improvements in correlation relative to tensile strength or tensile work alone.

Combined Data — Normal and Adverse Corrugating Conditions

To analyze the combined data, a preliminary screening of medium properties was performed. The dependent variable in this analysis was the composite average of the average flute height differences obtained under normal and adverse operating conditions. The results of the analysis indicated that the following properties were best related to flute height differences:

1. Tensile strength;
2. Formation;
3. Hygroexpansivity (92-25%).

The properties are listed in order of their selection in the stepwise regression. Inspection of the t values for the regression coefficients indicated that tensile strength and formation exhibited higher levels of statistical significance than hygroexpansivity.

On the basis of the above and the previously discussed results for each corrugating condition a number of multiple regressions were investigated for the combined data. The dummy variable technique discussed by Draper and Smith (10) was used to allow for the differences in high-low level between the normal and adverse corrugating conditions.

Referring to Table IX it may be noted that the two regressions exhibiting the highest, multiple R and lowest prediction errors were as follows:

$$\underline{Y} = 0.0478\underline{TE} - 0.102\underline{FO} + \begin{Bmatrix} 0.73 \text{ for normal corrugating conditions} \\ 2.10 \text{ for adverse corrugating conditions} \end{Bmatrix} \quad (1)$$

$$\underline{Y} = 0.069\underline{TE} - 0.085\underline{FO} - 2.16\underline{H9} - \begin{Bmatrix} 1.53 \text{ for normal corr. conditions} \\ 0.16 \text{ for adverse corr. conditions} \end{Bmatrix} \quad (2)$$

where

$\underline{Y}$ = average flute height difference, pt.

$\underline{TE}$ = tensile strength, lb./in.

$\underline{FO}$ = formation, unit

$\underline{H9}$ = hygroexpansivity (92-25%), %.

A comparison of observed and predicted values for Equations (1) and (2) may be found in Table X. It should be kept in mind that the caliper differences exhibit a relatively high coefficient of variation. In an earlier section it was noted that the 95% confidence limits on an average would be expected to be about $\pm$ 0.46 point. This should be kept in mind in considering the differences between observed and predicted values.

All factors in Equations (1) and (2) were significant at the 0.05 level or better. It may be noted, however, that Equation (2) exhibited only a small improvement in multiple R or prediction accuracy relative to Equation (1). The directions of the effects are as discussed in previous sections of the report — i.e., flute height differences increase as

(a) tensile strength increases;

(b) formation becomes less uniform;

TABLE IX

REGRESSION EQUATIONS FOR COMBINED NORMAL AND ADVERSE CORRUGATING CONDITIONS

No.	Regression Coefficients Var. 1	Var. 2	Var. 3	Constant Normal	Adverse	t Value Var. 1	Var. 2	Var. 3	F Ratio	Multiple Correlation Coefficient (R)	Average Prediction Error, %
17	0.0478TE	-0.102FO	--	0.73	2.10	3.57[a]	2.54[b]	--	29.4[a]	0.84	16.6
18	0.0690TE	-0.085FO	-2.16H9	-1.53	-0.16	4.21[a]	2.18[b]	2.08[b]	25.1[a]	0.85	15.4
19	0.0146TS	-0.081FO	--	1.63	3.00	2.80[a]	1.91[c]	--	25.3[a]	0.82	17.5
20	0.0361TR	-0.085FO	--	1.35	2.72	2.91[a]	2.03[b]	--	25.8[a]	0.82	17.0
21	0.0151TS	-0.078FO	-0.29H9	1.40	2.77	2.72[b]	1.76[c]	0.30	18.6[a]	0.82	17.3
22	0.0150TS	-0.075FO	+1.03H2	1.22	2.59	2.84[a]	1.74[c]	0.72	18.9[a]	0.82	17.3
23	0.0153TS	-0.068FO	-0.19CA	3.48	4.85	2.96[a]	1.59	1.33	19.8[a]	0.83	17.5
24	0.0148TS	-0.076FO	-0.011TC	2.02	3.39	2.79[a]	1.70[c]	0.41	18.6[a]	0.82	17.6
25	0.0149TS	-0.081FO	+1.99FR	1.10	2.37	2.82[a]	1.89[c]	0.53	18.7[a]	0.82	17.5

[a] Significant at the 0.01 level.
[b] Significant at the 0.05 level.
[c] Significant at the 0.10 level.

Note: Regression equation form $\underline{Y} = \underline{bx_1} + \underline{bx_2} \ldots \begin{cases} \underline{a} \text{ [for normal cond.]} \\ \underline{a} \text{ [for adverse cond.]} \end{cases}$

Symbols are defined below:

TE = tensile strength	H2 = hygroexpansivity (25-92%)
FO = formation	CA = caliper
H9 = hygroexpansivity (92-25%)	TC = transverse compression
TS = tensile work	FR = friction
TR = elastic work	Y = average flute height difference

TABLE X

COMPARISON OF OBSERVED AND PREDICTED VALUES

No.	Average Flute Height Difference, pt.					Average Flute Height Difference, pt.				
		Predicted					Predicted			
	Observed	Eq. (1)	Diff., %[a]	Eq. (2)	Diff., %[a]	Observed	Eq. (1)	Diff., %[a]	Eq. (2)	Diff., %[a]
	Normal Corrugating Conditions					Adverse Corrugating Conditions				
688	1.06	1.54	45.1	1.42	33.8	2.34	2.91	24.3	2.79	19.1
694	1.62	1.88	16.1	1.67	3.0	2.34	3.25	38.9	3.04	29.8
708	1.10	1.06	- 3.8	0.93	-15.0	2.50	2.43	- 2.9	2.30	- 7.9
710	2.60	2.54	- 2.4	2.56	- 1.6	4.56	3.91	-14.3	3.93	-13.9
714	1.86	1.59	-14.7	1.87	0.3	3.39	2.96	-12.8	3.24	- 4.6
717	1.62	1.19	-26.8	1.46	- 9.8	1.82	2.55	40.4	2.83	55.5
718	1.44	1.17	-18.9	1.28	-11.3	2.22	2.54	14.3	2.65	19.2
722	2.20	2.12	- 3.8	2.15	- 2.3	3.50	3.49	- 0.4	3.52	0.6
728	1.36	1.38	1.8	1.14	-16.0	2.66	2.75	3.5	2.51	7.9
732	2.02	2.09	3.6	2.18	7.9	3.80	3.46	- 8.9	3.55	- 6.6
762	1.48	1.71	15.7	1.42	- 4.1	2.90	3.08	6.2	2.79	- 3.8
733	2.18	1.66	-24.0	1.53	-30.0	3.22	3.03	- 6.0	2.89	-10.1
768	2.40	1.71	-28.9	1.88	-21.5	4.68	3.08	-34.3	3.25	-30.5
723	1.80	1.89	5.0	1.92	6.7	4.32	3.26	-24.5	3.29	-23.8
746	1.48	1.56	5.7	1.48	- 0.2	3.22	2.93	- 8.9	2.85	-11.6
793	1.53	1.79	16.9	1.93	25.8	2.66	3.16	18.7	3.29	23.8
779	1.45	1.73	19.5	1.95	34.4	3.20	3.10	- 3.1	3.32	3.7
751	1.65	1.72	4.2	1.72	4.2	2.38	3.09	29.7	3.09	29.7
802	1.48	1.72	16.4	1.52	2.6	2.28	3.09	35.6	2.89	26.6
790	1.60	2.30	43.7	2.30	43.4	3.18	3.67	15.3	3.66	15.2
831	2.04	1.62	-20.4	1.68	-17.6	3.55	2.99	-15.7	3.05	-14.1
	Composite average (normal and adverse)							16.6		15.4

(c) hygroexpansivity changes become larger (the $\underline{H}9$ values in this study were assigned a negative value to denote contraction).

It is speculated that the trend to higher caliper differences with tensile strength may occur because the corrugating stresses induce less plastic flow in the sheets with high tensile stress. As a result there may be greater strain recovery after passage through the corrugating labyrinth and consequently a greater possibility that differences in flute height may occur. It should be noted, however, that tensile strength is a failure property. Flute height differences or high-lows are not, in general, associated with failure of the medium though they often become more pronounced at speeds somewhat below the fracture speed. Thus, it seems difficult to entirely justify on physical grounds the correlation between tensile strength and caliper differences. On the other hand, other tensile properties such as modulus, stiffness, work, elastic work, stretch, recoverable stretch, and nonrecoverable stretch were, in general, inferior in correlation to tensile strength. Perhaps measures of the proportional limit load and strain or the slope of the load-deformation curve in the inelastic region would be worthwhile candidates for future investigation.

The apparent influence of formation appears to indicate that the uniformity of the sheet influences high-low flute formation. Nonuniformities in formation would be expected to influence both the degree of molding or separation of the upper and lower corrugating rolls and the response of the sheet to the tensile stresses in the plane of the sheet. Abrupt changes in caliper — e.g., a roll splice — are known to cause transient oscillatory displacements of the upper corrugating roll with resulting high-lows in the vicinity of the splice. On a much less pronounced scale, variations in sheet density both across the web and in the direction of travel, might result in smaller scale displacements of the upper roll and consequently in high-low flutes —

less pronounced than in the case of a roll splice but still evident. It would be of interest to study the dynamic fluctuations on formation — and perhaps caliper — on the moving web and their relationship to corresponding fluctuations in upper corrugating roll motion and high-lows.

Equations (1) and (2) indicate that hygroexpansivity is significantly related to caliper differences. However, it does not appear to be a strong factor inasmuch as the average prediction error only decreased from 16.6% for Equation (1) (without hygroexpansivity) to 15.4% for Equation (2) (with hygroexpansivity). While it does not appear to be a major factor in high-low flute formation, the moisture changes effected in the medium during corrugating perhaps justify consideration of the dimensional stability of the sheet under changing moisture conditions.

As mentioned in previous sections of the report, tensile work and elastic tensile work were significantly correlated with the caliper differences for both the normal and adverse corrugating conditions. With this in mind, two-factor regressions were performed using (a) formation and tensile work, and (b) formation and "elastic work". As shown in Equations (19) and (20) in Table IX, significant regression equations were obtained; however, they were slightly inferior in prediction accuracy to Equation (17) (tensile strength and formation). Efforts to improve the tensile work-formation relationship by consideration of hygroexpansivity, caliper, transverse compression and friction were not successful as the third factor failed to attain statistical significance at even the 0.10 level.

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APPENDIX I

FLUTE HEIGHT DIFFERENCE RESULTS FOR SINGLE-FACED BOARD

TABLE XI

SUMMARY OF INDIVIDUAL FLUTE HEIGHT RESULTS
(Normal corrugating conditions)

Roll No.	300 f.p.m. Flute Height, pt.	Av. Diff., pt.	Standard Deviation, pt.	Max. Diff., pt.	Percent Less Than: 3.0 pt.	4.0 pt.	5.0 pt.	450 f.p.m. Flute Height, pt.	Av. Diff., pt.	Standard Deviation, pt.	Max. Diff., pt.	Percent Less Than: 3.0 pt.	4.0 pt.	5.0 pt.
688	194.4	1.06	0.77	3.1	97.5	100.0	100.0	194.4	1.07	0.78	4.0	97.5	100.0	100.0
694	196.2	1.39	0.93	3.9	96.2	100.0	100.0	196.2	1.86	1.28	4.9	82.5	93.8	100.0
708	194.9	1.29	1.01	4.9	93.8	96.2	100.0	195.3	0.91	0.64	2.7	100.0	100.0	100.0
710	195.0	2.03	1.49	7.4	77.5	87.5	97.5	195.0	3.17	2.12	8.4	52.5	66.2	75.0
714	194.2	1.82	1.24	5.4	83.7	95.0	98.7	193.8	1.90	1.28	5.8	83.7	93.8	97.5
717	195.8	1.60	1.35	5.7	85.0	93.8	96.2	195.4	1.63	1.22	5.4	83.7	97.5	98.7
718	196.4	1.28	0.95	4.0	95.0	100.0	100.0	196.8	1.61	1.29	5.3	83.7	95.0	98.7
722	192.4	1.95	1.22	4.2	78.7	95.0	100.0	192.4	2.44	1.60	5.9	68.7	78.7	95.0
728	196.0	1.35	0.88	3.7	95.0	100.0	100.0	196.3	1.37	1.01	4.6	95.0	98.7	100.0
732	196.6	2.07	1.18	4.5	77.5	95.0	100.0	196.9	1.98	1.15	5.0	82.5	95.0	100.0
762	195.2	1.37	0.95	3.8	93.8	100.0	100.0	195.3	1.58	1.07	3.9	85.0	100.0	100.0
733	194.0	1.82	1.52	6.3	82.5	87.5	96.2	194.2	2.53	1.65	6.3	63.7	81.2	91.2
768	194.2	2.51	1.80	8.1	65.0	80.0	88.7	194.7	2.30	1.67	6.2	67.5	80.0	92.5
723	194.5	1.65	1.29	5.9	87.5	95.0	97.5	194.8	1.94	1.24	5.0	80.0	93.8	100.0
746	195.1	1.41	1.05	4.6	91.2	98.7	100.0	195.3	1.55	1.14	4.7	88.7	96.2	100.0
793	195.2	1.70	1.24	4.5	80.0	95.0	100.0	195.7	1.36	1.05	4.0	90.0	100.0	100.0
779	194.5	1.31	0.94	3.9	93.8	100.0	100.0	194.7	1.59	1.15	4.6	87.5	95.0	100.0
751	195.5	1.58	1.18	5.8	88.7	96.2	98.7	195.8	1.72	1.36	6.5	85.0	92.5	98.7
802	195.9	1.39	1.07	4.8	92.5	98.7	100.0	196.4	1.57	1.17	5.0	88.7	97.5	100.0
790	193.8	1.59	1.15	4.4	85.0	95.0	100.0	193.9	1.61	1.28	5.2	85.0	95.0	98.7
831	192.7	1.92	1.40	6.3	80.0	92.5	97.5	192.6	2.16	1.63	6.7	73.7	85.0	93.8

TABLE XII

SUMMARY OF INDIVIDUAL FLUTE HEIGHT RESULTS
(Adverse corrugating conditions)

	300 f.p.m.							450 f.p.m.						
	Flute	Av.	Standard	Max.	Percent Less Than:			Flute	Av.	Standard	Max.	Percent Less Than:		
Roll No.	Height, pt.	Diff., pt.	Deviation, pt.	Diff., pt.	3.0 pt.	4.0 pt.	5.0 pt.	Height, pt.	Diff., pt.	Deviation, pt.	Diff., pt.	3.0 pt.	4.0 pt.	5.0 pt.
688	195.1	2.50	1.58	6.7	65.0	81.2	93.8	194.1	2.18	1.68	7.0	73.7	85.0	93.8
694	197.5	1.96	1.41	5.8	73.7	93.8	98.7	197.7	2.71	1.80	8.0	66.2	82.5	90.0
708	195.1	2.16	1.49	5.5	73.7	86.2	95.0	194.7	2.83	2.07	7.9	55.0	75.0	82.5
710	197.5	4.05	2.88	11.7	45.0	57.5	62.5	196.1	5.08	3.19	12.8	35.0	42.5	47.5
714	194.5	3.28	2.71	10.6	56.3	68.7	76.2	193.8	3.50	2.23	7.9	42.5	63.7	77.5
717	197.5	1.87	1.26	5.3	85.0	92.5	98.7	197.3	1.77	1.41	6.2	83.7	92.5	96.2
718	198.5	2.02	1.46	6.0	75.0	91.2	96.2	198.5	2.43	1.60	6.5	67.5	85.0	92.5
722	192.7	4.14	2.92	11.8	43.8	57.5	68.7	191.2	2.85	3.22	17.5	67.5	80.0	86.2
728	197.5	2.40	1.81	9.4	66.2	82.2	92.5	197.0	2.93	1.69	7.5	58.7	75.0	90.0
732	197.7	3.46	2.45	10.6	55.0	67.5	77.5	196.9	4.13	2.86	11.0	41.2	51.2	66.2
762	196.4	2.38	1.71	9.3	70.0	85.0	93.8	196.2	3.43	2.52	13.0	52.5	61.2	81.2
733	196.0	3.24	2.18	9.6	53.7	65.0	76.2	195.6	3.21	2.52	11.3	51.2	66.2	76.2
768	196.3	3.65	2.22	8.4	46.2	63.7	71.2	195.7	5.71	3.51	13.5	26.2	42.5	51.2
723	195.7	3.67	2.62	11.6	46.2	60.0	70.0	194.8	4.97	3.36	14.9	32.5	47.5	60.0
746	196.8	2.97	1.75	7.5	55.0	71.2	86.2	196.0	3.47	2.47	10.8	46.2	60.0	75.0
793	198.0	2.74	2.11	7.8	58.7	72.5	82.5	197.6	2.58	1.82	9.1	67.5	82.5	91.2
779	194.8	2.86	2.00	8.6	57.5	75.0	87.5	193.4	3.53	2.86	11.6	53.7	63.7	66.2
751	196.8	1.91	1.57	7.5	75.0	92.5	95.0	196.5	2.84	2.18	8.5	65.0	70.0	80.0
802	197.7	2.02	1.79	8.7	73.7	83.7	95.0	196.7	2.55	2.13	12.0	68.7	81.2	88.7
790	193.8	3.28	2.33	9.1	48.7	68.7	80.0	192.8	3.07	2.59	10.6	56.3	72.5	81.2
831	192.0	3.23	2.16	8.3	50.0	66.2	78.7	189.9	3.87	2.37	9.3	43.8	61.2	70.0